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TRANSLATION

TESTING AIR-BREATHING ENGINES

By

V. M. Dorofeyev and V. Ya. Levin

FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

WRIGHT-PATTERSON AIR FORCE BASE

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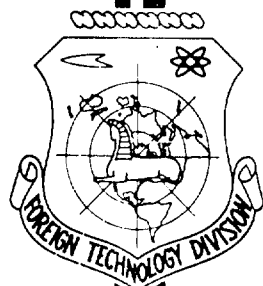
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TABLE OF CONTENTS

Various aspects of the testing of air-breathing jet engines are discussed in this book. Techniques and methods of processing data, and the measuring instruments, devices and equipment of laboratories and testing stations are described.

This book serves as a textbook for a course offered under the same title and is intended for students at higher schools of technical aviation; besides this, it will be useful to production engineers.

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- 1 -

FOREWORD

The construction of air-breathing jet engines (VRD) was first undertaken in the middle of the thirties in various countries. Much attention was paid to these engines during the Second World War, and the first series-produced jet aircraft were delivered prior to its conclusion. Extensive series production and operation of VRD were begun on a practical scale after the end of the war, and turbojet and turboprop engines have now gained the greatest acceptance.

The production of new engines made it necessary to modernize the methods of testing. During the early years of the development of jet aviation, VRD testing methods were not on a high level; the testing devices and measuring instruments were quite obsolete. After 1945, special testing stations and laboratories fitted out with modern measuring apparatus and the necessary equipment were set up in various countries.

Testing methods and techniques based on progress in aeronautical engineering have now evolved into a self-contained engineering disci·line.

Unfortunately almost no scientific literature for higher technical schools relating to this discipline has been published until now. The present book is a pioneer work in this field. The authors sought to make the reader fairly familiar with the theory and practice of VRD testing within the limits of this small volume; therefore, many problems are covered in as brief a fashion as possible.

Experimental and flight tests are covered for the first time in

- 2 -

the literature of aviation-engine testing. In this book special attention is devoted to the testing methods that are applicable to the most widely used types of VRD i.e., turbojet and turboprop engines.

The authors observed the work of beginner test engineers and came to the conclusion that in discussing problems of measurement it is better (within the limited volume of the text) to explain the principles of operation and construction of instruments than the methods of their use.

Problems involved in the design of testing installations and their parts are scarcely touched upon. Readers specializing in aircraft engine testing will have to study additional sources (see the bibliography at the end of the book).

At the request and under the editorship of the authors, Engineer S.N. Yerenine wrote Chapter 6, while Engineer V.S. Kondrusev wrote Chapter 7.

The authors are grateful to the Docents G.M. Gorbunov, L.B. Yevangulov, Yu, K. Zastel, to Candidate of Technical Sciences A. A. Lakshtovskiy and to Engineer Z. L. Kropp for many valuable remarks and suggestions with regard to the draft of the manuscript and during editing. The authors are also grateful to Engineer V. N. Pikul' and his coworkers in the Aircraft-Engine Engineering [TAD] Department of the Kuybyshev Aviation Institute for making changes in the manuscript. Much editing work on the manuscript was done by L.S. Skubachevskiy to whom the authors express their special thanks.

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- 3 -

Chapter 1

FORMS OF TESTING AIR-BREATHING JET ENGINES

Engine testing carried out in plants, in experimental design offices, and in scientific research institutes may be classified according to the location and purpose of the tests.

With regard to location the tests may be divided into ground and flight tests.

The ground tests cover all experiments carried out on the ground; these tests include experiments with apparatus simulating the altitude and speed conditions of flight.

Flight tests are engine tests during flight in special aircraft, i.e., flying laboratories, in test and series-produced aircraft and in pilotless aircraft.

Depending on the purpose, testing is divided into scientific research, experimental, and routine tests (see chart). Now we shall consider the features of each aspect of testing.

1. SCIENTIFIC RESEARCH TESTING

Scientific research tests may differ in aim, but their main problem is to study and analyze the phenomena and processes occurring in the engine or in its component assemblies. Commonly, scientific research testing is carried out to study thermodynamic and gasdynamic processes in the engine, the operation of single units, the fuel and its combustion, and to analyze the engine characteristics, the strength of its parts, etc.

When an engine is designed according to a radically new principle,

the scientific research work may be complicated by insufficient know-
ledge of some physical phenomena occurring in the engine and by the
frequent lack of appropriate measuring apparatus.

Thermodynamic and gasdynamic investigations of the intake
devices, compressors, combustion chambers, turbines, and engine noz-
zles, as well as the determination of their characteristics, may be
carried out under natural conditions in special laboratories with com-
plex and cumbersome equipment requiring considerable electrical power.
The theory of similarity makes is possible to conduct approximate
tests of engine elements on models. Tests on models can be carried
out with notably less powerful equipment, thus offering important
economic advantages.
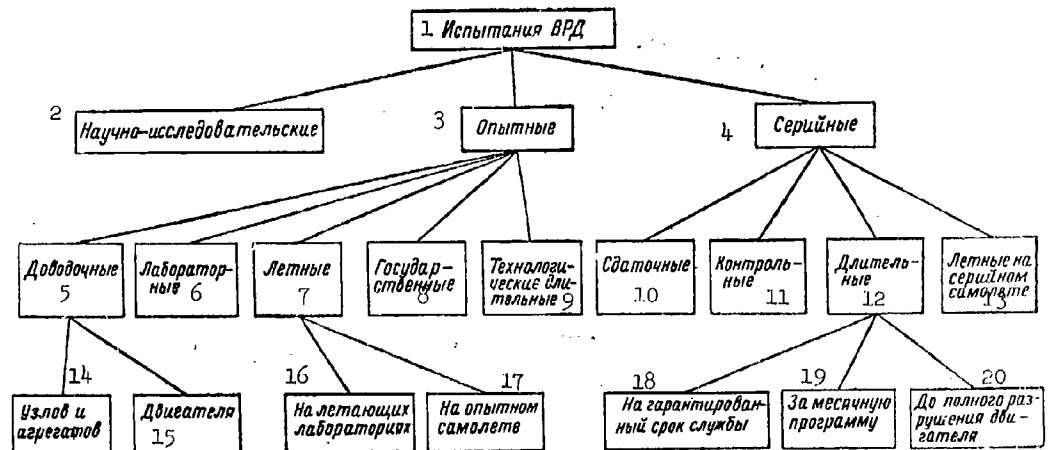
Classification of tests. 1) Testing of VRD; 2) scientific research;
3) experimental; 4) series; 5) adjustment; 6) laboratory; 7) flight;
8) state; 9) long-run engineering; 10) delivery; 11) control ; 12)
long-run; 13) flight tests in series-produced aircraft; 14) units
and assemblies; 15) engine; 16) in flying laboratories; 17) in ex-
perimental aircraft; 18) for guaranteed service life; 19) according
to a monthly program; 20) to complete destruction of engine.

The ruggedness of engines and the strength of their units and
parts are commonly studied in special laboratories.

The results of scientific-research testing provide the possibi-

...lity of understanding the nature of the operational processes that occur in the engine, of determining the factors responsible for the phenomena occurring and of improving the accuracy and completeness of the existing theory and methods of design. In individual cases, test results may be used as a basis for developing new methods of design and new theoretical generalizations.

Scientific-research tests are usually carried out in scientific research institutes, in higher schools of education, and sometimes in experimental design offices.

2. EXPERIMENTAL TESTING

The principal aim of experimental testing is to determine the operational cycle and design of the engine. Experimental tests utilize the results of scientific-research tests. The absence of exact theory for some phenomena occurring in the engine does not halt experimental work, though it does slow it down. Experimental engine tests involve adjustment, laboratory, flight, state, and long-run engineering tests. Adjustment tests are carried out in two stages, i.e., assemblies and single units are inspected in plant laboratories and the complete engines are tested at experimental test stations. These tests are mostly carried out in the environment.

Adjustment tests include the following;

1) Adjusting the engine cycle;

2) Putting the finishing touches on the design of single units and assemblies;

3) checking the correctness of the choice of materials and the technignes of parts fabrication;

4) determining the service life of the engine and finding means to lengthen it;

5) turning the engine parameters for various regimes to values

- 6 -

in the customer's specifications.

Independent of the adjustment tests on engines, performed in experimental plants, laboratory tests are carried out in scientific research institutes i.e., in high-altitude laboratories equipped with heat and pressure chambers and wind tunnels, by means of which the required flight conditions of height and speed can be simulated on the ground, and by means of which corresponding engine characteristics can be recorded. Sometimes special tests according to a program which takes account of definite operating conditions (low or high temperatures, desert conditions, rain, etc.) are carried out in these laboratories.

Once the adjustment and laboratory tests have been successfully completed, experimental flight tests begin. As a rule, experimental flight tests are first carried out on special aircraft. i.e., flying laboratories. Flying-laboratory tests are sometimes conducted before engine adjustment testing has been concluded. Flight safety is assured by the presence of series-produced powerplants on the flying laboratory, and by reducing the overhaul period for the engine under test. Flying laboratories generally limit the possibilities of testing engines with respect to flight speed and altitude.

After the operation of an engine has been carefully checked in the flying laboratory, testing is continued on the experimental aircraft designed for the given engine. These tests serve to determine the operational reliability of the powerplant as a whole and to determine whether it corresponds to the technical specifications.

It is natural that new engine defects may be discovered during the laboratory and flight tests. Such defects must be eliminated, after which the engine is again tested.

Upon completion of the adjustment tests, the engine undergoes

state inspection tests. These tests are carried out on the ground at the testing stations of an experimental plant in accordance with a special program. The regimes, duration, and sequence of the tests are chosen so that the conditions of engine operation correspond as closely as possible to the conditions under which it will have to operate later on. For instance, turbojet and turboprop engines are tested in nominal [rated], augmented (take-off and combat), and cruising re gimes.

The nominal regime corresponds to the rated regime of the engine. The engine should work reliably in this regime for a considerable part of its service life. Tests in this regime are carried out with continuous running for periods of 30 minutes.

Thrust augmented regimes (take-off and combat) are achieved by increasing the number of revolutions of the turbine shaft, increasing the gas temperature behind the turbine, or by adding an afterburner. These regimes can also be achieved by combined methods of affecting the engine cycle. Thrust augmented regimes are employed temporarily for the take-off of an overloaded aircraft or to increase briefly the flight speed or rate-of-climb. The engine should operate reliably in these regimes for 5 - 10 minutes, subsequently bring switched to an easier [lighter] regime.

The continuous running time in nominal and augmented regimes may change within a given range, depending on the designation of the air-craft in which the engine is used.

The cruising regime is the one in which the number of shaft re-volutions for the turbine and the gas temperature behind the turbine are lower than in the nominal [rated] regime. For TVD [turboprop engines] the cruising regime is achieved by changing the angle-of-attack of the propeller blades appropriately, while maintaining a constant

- 8 -

number of engine revolutions. The duration of continuous operation in this regime is unlimited.

The state inspection-test schedules for various engines of the same type may differ from one another as regards regime and duration, and they are based on the ultimate purpose for which the engine is to be used. The findings of the State Commission on the successful completion of the tests ~~ ~~~~ ~~ '' ...is for directing the series production of the engine.

The work of constantly seeking new improvements in the engine does not come to an end when series production starts. Experimental design offices (OKB) attached to the prime series-production plants seek to improve the technical data of the engines delivered by the plant and to lengthen their overhaul periods. For this purpose, long-run tests are periodically carried out on engines at the testing stations of the series-production plants, and necessary changes in the construction an operating conditions are introduced. These tests are known as long-run engineering tests and are performed according to a special program worked out by the OKB. Successful completion of the tests gives the plant the right to make the required changes and to begin the production of a new series of engines.

3. SERIES TESTING

Series tests are carried out under environmental conditions at the testing stations of the production plants. The following kinds of series tests are distinguished: delivery, control , long-run and flight.

Every engine delivered by the plant undergoes delivery tests. The tests are carried out to check the quality of the engine, to see to it that the parts are run in, to check on the correctness of assembly, and to adjust engine operation to the various regimes in order to

- 9 -

comply with the main data of the technical specifications.

If the delivery-test results are found to diverge from the given basic engine data, or if a defect which might lead to an accident is discovered, testing is stopped. When the defects have been eliminated, the engine is put through the delivery tests once again.

Each engine is dismantled after delivery testing and all its parts are inspected for defects, after which the engine then undergoes controltests of its operation in all regimes stipulat . in the technical specifications. The customer accepts the engine if all results of the control test are satisfactory, and the engine is then sent on for shipment. There must be no irregularities of any kind during the course of the control tests. If defects are discovered, the control test is cancelled.

Long-run series tests are divided into:

1) testing the guaranteed service life of the engine up to its first overhaul;

2) testing the engine according to a monthly program (period of testing is 50% of the guaranteed overhaul period);

3) testing the engine to total destruction.

Long-run tests are carried out according to a program of the same type as the state inspection tests, except for measuring certain special characteristics.

The frequency of tests depends on their purpose. Tests on the service life guaranteed by the plant are carried quarterly and the monthlyprogram tests are carried out once a month. The dates when long-run tests are carried out may be changed in accordance with the engine delivery program.

It is, moreover, possible to combine tests. For instance, the test on the engine service life guaranteed by the plant up to the

- 10 -

first overhaul is considered a part of the current monthly testing program as well. In this case, the decision as to the delivery for that month is based on the results of testing the guaranteed service life. Satisfactory results of the long-run tests on the series give the plant the authority for further delivery of engines in the given month .

Long-run tests are carried out in stages; the intervening periods are kept within the time limits necessary for carrying out adjustment operations.

Long-run tests are regarded as unsatisfactory if during the course of the tests or as part of the inspection subsequent to the test certain parts whose breakdown or damage entails the risk of engine failure are found to be inoperative. In this case the delivery of engines from the factory is curtailed until positive results are obtained from repeat long-run tests which are carried out after the elimination of the defects.

Long-run testing of series-produced engines to complete destruction makes it possible to check the reliability and determine the service life of engine parts and assemblies, to refine maintenance techniques, to check the quality and nomenclature of repair tools and devices, to refine the tables of tolerances for maximum wear of components and clearances in assemblies of rebuilt engines, to refine the list of spare parts stocks for the first, second, and subsequent overhauls.

All engines in series production for the first time or those which have been significantly changed, are tested to complete destruction. As a control, engines which have passed the tests for the service life guaranteed by the plant are selected. The tests are carried out over periods which are equal to the overhaul period of the

engine. After each period the engine is overhauled, during which the parts are inspected for flaws . The worn-out parts are replaced with new ones from the stock of spare parts. The engine is overhauled in accordance with the repair techniques and tools specially produced by the plant for maintenance purposes. The test is considered to be fin- :hed if a considerable number of parts break down; the items and their number are specified in the technical specifications.

Increasing the overhaul period of an engine that has yielded good operational results is of great importance. To solve this problem, a group of engines is selected and these have been run under operating conditions for the lifetime guaranteed by the plant. Some of the engines in this group are sent to the manufacturing plant for inspection and determination of defects, and for additional tests.

The results of the inspection and determination of the defects of the selected engines are used in the determination of the duration of the additional tests, together with the results of the tests-to-destruction previously carried out on the engines. If the results of the additional tests are satisfactory, flight tests on the engines remaining from the group are allowed in aircraft, to last for a period of time corresponding to the additional service life.

Successful flight tests give the plant the right to increase the overhaul periods of the delivered engines. Sometimes these tests are known as operational tests.

Chapter 2

ELEMENTS OF METROLOGY

The development of a system of measures, measurement instruments, measurement methods, and the processing of observational results relies on the achievements of many branches of science and engineering. Contemporary methods of processing measurement results were developed primarily during the first half of the 19th century.

In the USSR the Committee of Standards, Measures, and Measurement Instruments, and its branches, are responsible for the maintenance of uniformity and reliability of measures. Moreover, there are official control agencies to check on the measures and measurement instruments used in factories and research institutions; these measures and measurement instruments must be registered at the Committee of Standards, Measures, and Measurement Instruments.

The branches of the Committee maintain a check on standard measures and measurement instruments, as well as on instruments employed for production control (if no official control agency exists at the particular factory in question).

The methods of checking measures and measurement instruments have been spelled out in the document entitled "Temporary Rules 12-54 for the Organization and Verification of Measures and Measurement Instruments." Plants [enterprises] producing measures and measurement instruments submit test specimens of the latter to the Committee of Standards, Measures, and Measurement Instruments for its approval.

International standards are used to verify measures and measure-

- 13 -

ment instruments for absolute precision. The State standards of measures, prepared with metrological accuracy, are held to be true magnitudes.

1. MEASURES, MEASUREMENT INSTRUMENTS, AND THEIR INACCURACIES

A measure is defined as a "body" or device which represents a physical reproduction of [certain] measurement units or fractions of these. Thus, for example, weights represent measures of mass and rays of light represent measures of length (meters, centimeters, etc., are also measures of length).

In the majority of cases it is impossible to undertake a direct comparison of measured magnitudes and measures. For this reason measurement is performed with the aid of measurement instruments that permit the convenient and sufficiently accurate comparison of measured quantities with the adopted units of the measure.

All measures and measurement instruments are divided into two groups:

1) standard measures and standard measurement instruments;

2) working measures and working measurement instruments.

Standard measures and instruments are used for purposes of reproducing and safeguarding the adopted measurement units, as well as fractions or multiples of the latter. Occasionally standard instruments may be employed for purposes of exact measurements in experimental projects. Working measures and instruments include all measures and instruments with the exception of the standards.

A measurement result read off from a measure or instrument scale is known as a nominal result. The value of the measured magnitude obtained by means of the more exact standard instrument or measure is known as the true value. If the measurements are being conducted by means of standard instruments, the true magnitudes are determined by

means of even more exact instruments.

The difference between the nominal and true values of a magnitude is known as the absolute error of the measure or instrument and may be represented in the following form:

$$\Delta = \alpha_n - \alpha_d,\qquad\qquad(1)$$

where α_n is the nominal value; α_d is the true value.

The absolute correction factor for the measure or instrument is obtained by taking the error, but opposite in sign:

$$\delta = -\Delta = \alpha_d - \alpha_n.\qquad\qquad(2)$$

It is clear that

$$\alpha_d = \alpha_n + \delta.\qquad\qquad(3)$$

We can see from Expression (3) that the true value of a measured magnitude is the algebraic sum of the nominal value of the magnitude and the correction factor.

For example, let us assume that we have two working rulers each 100 mm long. A comparison with the standard measure showed that the true length of the first ruler was 100.1 mm, while the true length of the second ruler was 99.8 mm. Thus the absolute error of the first ruler was

$$\Delta_1 = 100 - 100,1 = -0,1 \text{ mm}$$

while that of the second was

$$\Delta_2 = 100 - 99,8 = 0,2 \text{ mm}.$$

The correction factor for the first ruler was equal to 0.1 mm, while that of the second ruler was minus 0.2 mm.

In addition to absolute errors, relative errors are frequently determined. Relative errors are calculated in % according to the following formulas:

the true relative error

- 15 -

$$\Delta_\pi = \frac{a_\pi - a_\pi}{a_\pi} \cdot 100; \qquad\qquad (4)$$

the nominal relative error

$$\Delta_\pi = \frac{a_\pi - a_\pi}{a_\pi} \cdot 100; \qquad\qquad (5)$$

the reference relative error

$$\Delta_\pi = \frac{a_\pi - a_\pi}{a_\pi} \cdot 100, \qquad\qquad (6)$$

where α_p is the limit value of the instrument scale.

Example. The gas pressure behind the turbine was measured during an engine test by means of two manometers. The working manometer used by the mechanic showed a pressure reading of 2.1 kg/cm^2 (the nominal value). At the same time, the standard manometer gave a reading of 2.15 kg/cm^2 which is regarded as the true magnitude.

The absolute measurement error is equal to

$$\Delta = p_\pi - p_\pi = 2.10 - 2.15 = -0.05 \text{ kg/cm}^2.$$

The correction factor will be

$$\delta = p_\pi - p_\pi = 2.15 - 2.10 = 0.05 \text{ kg/cm}^2.$$

The relative errors in this case will be equal to

$$\Delta_\pi = \frac{-0.05}{2.15} \cdot 100 = -2.32 \text{ %}$$

and

$$\Delta_\pi = \frac{-0.05}{2.10} \cdot 100 = -2.38 \text{ %}.$$

Generally, the quantities Δ_d and Δ_n are close to one another in measurement practice and the relative error can be determined both with respect to the nominal and the true value of the measured magnitude, making no distinction between these.

In addition to the indicated absolute and relative errors, we also employ the concept of permissible error (absolute or relative). The maximum instrument error stated in the manual is referred to as

- 16 -

the permissible error.

An important index of instrument quality is the constancy of its readings, this being determined by the variation. The greatest difference between the measurement results obtained with one and the same quantity, these measurements being carried out under identical conditions, is known as instrument variation.

An important characteristic of an instrument is its sensitivity which is determined from the following formula:

$$S = \Delta n/\Delta A, \qquad (7)$$

in which Δn represents the number of scale divisions; ΔA represents the number of units corresponding to Δn in the measured quantity.

Measures and measurement instruments are classified in terms of the kind of quantity being measured, the operating principle, the method of transmitting the readings, dimensions, precision, area of application, etc.

Instruments are divided, in terms of the manner of obtaining the measured magnitude, into comparator, indicating, and integrating instruments.

Comparator instruments are those which make it possible to compare a measure against the quantity being measured (i.e., a measure must necessarily be included as part of the comparator). As an example of a comparator we can cite a pan balance (the object to be measured is placed on one pan, the measures being collected on the other — weights to balance the quantity be measured).

Indicating instruments refer to those which make it possible to read the value of the measured magnitude directly. The majority of instruments in use belong to this category. Indicating instruments include dial scales, clocks, manometers, dynamometers, thermometers, etc.

To the class of integrating instruments belong the adder instru-

- 17 -

ments (total-revolution counters, liquid and gas flowmeters, meters to measure the consumption of electric energy, planimeters, etc.).

In terms of the recording method, instruments are divided into:

1) instruments with direct reading (manometers, dynamometers, etc.);

2) self-recording (i.e., with automatic recording of readings);

3) control instruments (i.e., instruments which measure the parameters of a process and intervene in its progress through appropriate devices);

4) short- and long-range instruments.

The accuracy of an instrument is characterized by the magnitude of the maximum reference relative error or the precision class. For example, an instrument of the 0.5 class exhibits a permissible reference relative error of $\pm 0.5\%$. All instruments are classified [grouped into classes] on the basis of their precision.

Measures and instruments are also designated as "laboratory" (for accurate laboratory measurements) and "industrial" (for less-precise measurements). When measuring with laboratory instruments it is necessary to bear in mind the correction factors that must be employed with the readings of the instruments, while in some cases it is necessary to carry out special tests to determine the measurement accuracy. When measuring with industrial instruments the measurement accuracy is given in advance in the rating data for the instrument.

Standard measures and instruments are divided into:

1) standards;

2) standard measures and instruments of limited accuracy (most frequently, simply standard measures and instruments).

Standards are defined as the measures and instruments of the highest (metrological) accuracy. The accuracy of the standards is main-

tained in view of their infrequent utilization and their storage under special conditions. Standard measures and instruments may exhibit lower accuracy and are verified by means of working standards.

The classification of standards, standard measures and instruments, and the methods of achieving and maintaining their accuracy are examined in detail in metrology courses.

2. MEASUREMENTS

We distinguish direct and indirect measurements. In direct measurements the sought quantity is determined directly by means of a measure or instrument. Indirect measurements are used when direct measurements are difficult or impossible. As an example of an indirect measurement we can cite the example of the measurement of power when for the derivation of a numerical value for this magnitude it is necessary individually to measure the revolutions and the moment, the value of the power being derived from the appropriate formula.

Direct measurements are most frequently carried out in the following ways:

1) by the method of indirect estimation (for example, the measurement of temperature by means of a mercury thermometer, the measurement of weight on scales, etc.);

2) by the differential method (the difference between the sought quantity and some known magnitude is measured);

3) by the null method (the effect of the quantity being measured is offset by a countereffect known in advance). An example of the application of the null method is given by the weighing [of an object] on equal-arm scales, the measurement of the emf of a thermocouple by means of a potentiometer, the measurement of the reaction force of a combustion chamber by setting the needle of the thrust measuring device to zero, etc.

- 19 -

3. MEASUREMENT ERRORS

Errors always occur in measurement, and these can be divided into subjective and objective. Subjective errors depend on the characteristics of the observer, the shortcomings of his sense organs, and the inadequacies of his nervous system.

First of all let us present examples of visual errors. The distance between points a and b in Fig. 1 seems to be substantially greater than between points b and c. It is easy to prove, however, that the points are equidistant from one another.
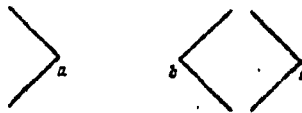
Fig. 1. Estimation of
the distance between
the points.
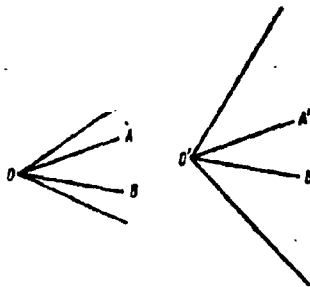
Fig. 2. Estimation of
angles.

Fig. 3. Es-
timation of
shape.

The angle AOB in Fig. 2 seems greater than the angle A'O'B'. In actual fact they are equal.

A number of vertically positioned circles are presented in Fig. 3. It seems that their right-hand edges follow a curve that bends to the left. It is quite easily demonstrated that the right-hand edges of these circles lie on a straight line.

An observer's organic visual and aural imperfections also affect

- 20 -

In experimental work fast reaction to a given signal is extremely important. Experiments have demonstrated that the reaction (the movement of a finger) after the application of an intense sound signal occurs after a lapse of 0.082-0.195 sec, whereas the reaction occurs 0.06-0.07 sec later in the case of a weak signal.

The cited data should convince the reader of the necessity of a critical attitude not only to the measurement methods and the instruments, but to the characteristics of the individuals participating in the measurement operations.

The factors responsible for the appearance of objective errors include instrument inaccuracies, limited measurement time, a time lag on the part of the instruments and the experimental installation as a whole, and the influence exerted by the surrounding medium on the instruments and the installation.

In addition, we also distinguish systematic and random errors, as well as complete misses.

Systematic errors may be attributed to various factors and can be classified as:

1) instrumental, i.e., occurring as a result of instrumental inaccuracies;

2) setting, i.e., attributable to the improper setting of the measuring equipment (nonlevel setting, misalignment, etc.);

3) personal, i.e., resulting from certain characteristics of the observer (improper color evaluation, slow reaction, hearing imperfections, etc.);

4) measurement-method, i.e., in the measurement, for example, of the stagnation temperature of a gas stream by means of thermocouple with an open junction, etc;

5) theoretical, i.e., originating as a result of the application of inaccurate or erroneous formulas for the evaluation of experimental data.

Systematic errors cannot be eliminated completely, but in experimental practice every effort is always made to eliminate these errors or to take them accurately into consideration.

Instrumental and setting errors can be reduced by [improved] design methods, the calibration of the instruments (comparison of the instrument readings with the standard and the introduction of corresponding correction factors into the readings of the working instruments), proper setting up of the instruments and protecting them against vibrations, dust, and jolts. The instructions for the setting up of instruments are generally given in the corresponding manuals.

Personal errors can be reduced by the selection of "operators" who satisfy given requirements. When this is impossible, every effort should be made to develop automatic and semi-automatic measurement systems whose work is independent of the characteristics of the "operator."

Theoretical errors and errors in the measurement method may be eliminated or reduced by a detailed preliminary study of the theory of the phenomenon, of the chosen measurement system, of the instruments to be used, and of the experience of other experimenters.

Those systematic errors that have been taken into consideration in advance exert no influence on the final test result.

Random errors are unavoidable. There are no explanations for their appearance in any specific case. The theory of errors is concerned with the study of these errors.

"Misses" are excessively great errors brought about by inattentiveness on the part of the observer or irregularities in the measure-

ment systems. In evaluating test results "misses" are eliminated from consideration.

4. EVALUATION OF EXPERIMENTAL DATA BY THE METHOD OF LEAST SQUARES

To derive the most accurate values for the measured quantities, the method of least squares is used to evaluate the observational results. The fundamentals of this method were derived by Gauss for the evaluation of astronomic observations in the year 1808. The method of least squares gradually found application in other fields of knowledge.

The method of least squares exhibits particularly great significance in the adjustment [running in] of precise research equipment and in gasdynamic investigations. For the evaluation of experimental results with this method it is absolutely necessary to have a substantial number of experimental points (at least 10 measurements must be carried out for each regime), and this restricts the application of this method for tests on full-scale engines. Let us undertake a brief examination of the fundamentals of the method of least squares.

The theorem of probability multiplication

The ratio of the number of events of an occurrence to the number of all equally possible events gives the probability of an event.

Thus, for example, if out of 100 tested engines 5 engines exhibited a nonuniform temperature field, the probability of engines exhibiting this defect in the following lot of engines is equal to 0.05 (if, of course, no measures are implemented to eliminate this shortcoming).

For the validation of the method of least squares the theorem of probability multiplication is very significant.

Theorem. The probability of the simultaneous occurrence of two independent events is equal to the product of the probabilities of the occurrence of these two independent events.

Let the probability of the first event be given by

- 23 -

$$p_1 = \frac{m_1}{n_1}$$

and let the probability of the second event be given by

$$p_2 = \frac{m_2}{n_2}.$$

The total number of equally possible events is equal to $n_1 \cdot n_2$, since any of the events of the second group can correspond to each event of the first group.

The number of favorable cases is equal to $m_1 \cdot m_2$ for the same reason. Since the simultaneous occurrence of two independent events is also an event,

$$p = \frac{m_1 \cdot m_2}{n_1 \cdot n_2} = p_1 \cdot p_2. \tag{8}$$

which is what we wanted to prove.

Distribution of random errors

The theorem of probability multiplication and the following axioms serve as the foundation for the derivation of a formula to express the distribution of random errors (the Gaussian [or normal] distribution).

1. Errors equal in absolute magnitude but differing in sign occur with identical frequency.

2. The frequency of occurrence for small errors is greater than the frequency of occurrence for large errors. Extremely large errors are not encountered.
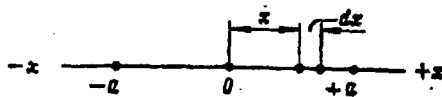
Fig. 4. With reference to the derivation of the Gaussian distribution [the law of error].

These axioms are based on the wealth of experience in investigations of the most varied branches of science. In our derivation of the

Gaussian distribution let us assume that N measurements of the same quantity have been carried out. The greatest errors noted during this procedure were +a and −a. Let us plot the quantities +a and −a on the horizontal error axis (the x-axis). We will divide the segment between points −a and +a (Fig. 4) on the error axis into a large number (n) of parts. Of the total number N of measurements some number dN of the measurements will exhibit errors falling within the segment dx separated by x from the origin 0 of the coordinate system. The distance x in this case characterizes the magnitude of the error. We can assume that

$$dN = Nf(x)dx,$$ (9)

where $f(x)$ is the sought function expressing the error distribution; N is the known number of measurements.

The probability of the occurrence of x errors on the dx segment will be

$$dp = \frac{dN}{N} = f(x)dx.$$

It follows from the first axiom which we adopted at the beginning of our derivation that

$$f(x) = \varphi(x^2),$$

since errors symmetrical with respect to the origin 0 of the coordinate system are encountered with identical frequency. Thus after substitution we will obtain

$$dp = \varphi(x^2)dx.$$ (10)

To determine the form of the function $\varphi(x^2)$ let us examine the problem associated with firing at a target. Let the "marksman" seek to hit the center of a target, the center being coincident with the origin 0 of the coordinate system (Fig. 5). Experience shows that the "hits" for a good "marksman" in the target bunch up around the center

- 25 -

− ı

of the target, with fewer and fewer "hits" being encountered with in-creasing distance from the center. The probability that of N shots dN will strike the hatched rectangle $\underline{m}$ is given by

$$dp = \frac{dN}{N} = \varphi(x^2)\,d\lambda\,\varphi(y^2)\,dy. \qquad (11)$$

Now let us turn to the rotated coordinate axes ξ and η, the ξ-axis passing through the center of the rectangle $\underline{m}$, as shown in Fig. 6.
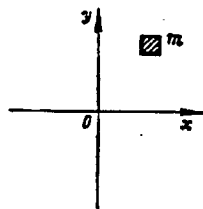
Fig. 5. Target.
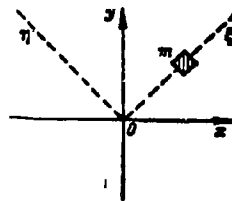
Fig. 6. Target with turned coordinates.

It is clear that

$$\xi^2 = x^2 + y^2$$

and the probability

$$dp = \varphi(0)\,d\eta\,\varphi(\xi^2)\,d\xi, \qquad (12)$$

but

$$\varphi(\xi^2) = \varphi(x^2 + y^2),$$

in which case

$$dp = \varphi(0)\cdot d\eta\,\varphi(x^2 + y^2)\,d\xi. \qquad (13)$$

Assuming $d\xi\,d\eta = dxdy$, we will obtain

$$dp = \varphi(0)\,\varphi(x^2 + y^2)\,dx\,dy. \qquad (14)$$

Subsequently combining Expressions (11) and (14), we will find that

$$\varphi(0)\,\varphi(x^2 + y^2) = \varphi(x^2)\,\varphi(y^2). \qquad (15)$$

Thus we obtained a functional equation which makes it possible for us to determine the form of the function $\varphi(x^2)$. Let us carry out

- 26 -

the following substitution: $x^2 = u$; $y^2 = v$; $\varphi(0) = c$; in this case Eq. (15) assumes the following form:

$$c\varphi(u+v) = \varphi(u)\varphi(v). \tag{16}$$

It is clear from the foregoing that $\underline{u}$ and $\underline{v}$ are independent of one another and may assume any values. Let $v = k$, where $\underline{k}$ is a constant. Then Eq. (16) assumes the following form:

$$c\varphi(u+k) = \varphi(u)\varphi(k). \tag{17}$$

Differentiating Eq. (17) with respect to $\underline{u}$, we will obtain

$$c\varphi'(u+k) = \varphi(k)\varphi'(u). \tag{18}$$

Dividing Eq. (18) by (17)

$$\frac{\varphi'(u+k)}{\varphi(u+k)} = \frac{\varphi'(u)}{\varphi(u)} \tag{19}$$

and let us prove that these fractions are equal to some constant number for the given case.

Assuming that

$$\omega(u) = \frac{\varphi'(u)}{\varphi(u)}$$

and

$$\omega(u+k) = \frac{\varphi'(u+k)}{\varphi(u+k)},$$

we will obtain

$$\omega(u) = \omega(u+k). \tag{20}$$

Equation (20) is valid for any values of $\underline{u}$ and $\underline{k}$, including the case in which $u = 0$.

The function $\omega(k)$ remains valid for any values of $\underline{k}$, i.e., $\omega(k) = $ const. Consequently, the function $\omega(u) = $ const is independent of $\underline{u}$. Hence it follows that

$$\frac{\varphi'(u)}{\varphi(u)} = b. \tag{21}$$

After integration

$$\ln\varphi(u) = bu + \ln C,$$

- 27 -

whence

$$\varphi(u) = Ce^{bu} \qquad (22)$$

or

$$\varphi(x^2) = Ce^{bx^2}. \qquad (23)$$

In accordance with the second axiom which states that the function $\varphi(x^2)$ must diminish with an increase in x, we can assume $b = -1/h^2$ to be constant and we will obtain

$$\varphi(x^2) = Ce^{-\frac{x^2}{h^2}}. \qquad (24)$$

It is clear that all errors in the N tests will lie along the error axis (the x-axis) in the range from $-\infty$ to $+\infty$, i.e.,

$$dN = N\varphi(x^2)\,dx$$

and

$$N = N\int_{-\infty}^{+\infty}\varphi(x^2)\,dx,$$

whence

$$\int_{-\infty}^{+\infty}\varphi(x^2)\,dx = 1. \qquad (25)$$

The integral

$$\int_{-\infty}^{+\infty}e^{-\frac{x^2}{h^2}}dx = h\sqrt{\pi}, \qquad (26)$$

and consequently

$$C = \frac{1}{h\sqrt{\pi}}.$$

Thus

$$f(x) = \varphi(x^2) = \frac{1}{h\sqrt{\pi}}e^{-\frac{x^2}{h^2}}. \qquad (27)$$

The formula expressing the Gaussian distribution takes the form:

$$dp = \frac{1}{h\sqrt{\pi}}e^{-\frac{x^2}{h^2}}dx. \qquad (28)$$

- 28 -

The as yet unknown quantity $\underline{h}$ can be found in the following manner. The number of errors on the segment dx, situated at a distance $\underline{x}$ from the origin of the error axis, is equal to

$$dN = N f(x)\,dx = \frac{N}{h\sqrt{\pi}} e^{-\frac{x^2}{h^2}}\,dx. \qquad (29)$$

In the summing of the squares of the errors, the sum will include the following expression:

$$x^2\,dN = N\,\frac{1}{h\sqrt{\pi}}\,x^2 e^{-\frac{x^2}{h^2}}\,dx.$$

The theoretical magnitude of the sum of the squares of the errors can be determined by integrating the previous expressions in the range from $-\infty$ to $+\infty$:

$$S_t = \frac{N}{h\sqrt{\pi}} \int_{-\infty}^{+\infty} x^2 e^{-\frac{x^2}{h^2}}\,dx = N\,\frac{h^2}{2}. \qquad (30)$$

whence it follows that

$$h^2/2 = S_t/N. \qquad (31)$$

Denoting the error by

$$\varepsilon_i = l_i - L,$$

where l_1 is the measured value of the quantity; L is the true value of the quantity, we will obtain

$$S_t = \varepsilon_1^2 + \varepsilon_2^2 + \ldots + \varepsilon_N^2$$

and

$$h = \sqrt{2\,\frac{\varepsilon_1^2 + \varepsilon_2^2 + \ldots + \varepsilon_N^2}{N}}. \qquad (32)$$

The quantity

$$\mu = \sqrt{\frac{\varepsilon_1^2 + \varepsilon_2^2 + \ldots + \varepsilon_N^2}{N}} \qquad (33)$$

is known as the mean square error of the theories of measurements or simply as the mean error of the measurement series.

- 29 -
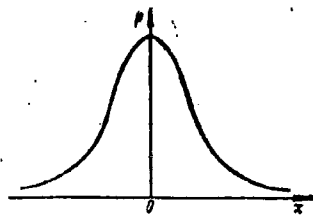
Fig. 7. Distribution of random errors.

Thus the formula representing the Gaussian distribution takes the following form:

$$dp = \frac{1}{\mu\sqrt{2\pi}} e^{-\frac{x^2}{\mu^2}} dx. \qquad (34)$$

The derived expression for the distribution of random errors can be represented in the form of a curve (Fig. 7).

Calculations show that the magnitudes of the errors in half the measurements (0.5N) lie within the range from -0.674μ to $+0.674\mu$. The shape of the curve for the Gaussian distribution is a function of the value of the mean square error of the measurement series. Many investigators verified the Gaussian distribution experimentally and confirmed its validity. In the presence of noticeable systematic errors the curve shifts and becomes nonsymmetrical with respect to the coordinate origin.

If we use the Gaussian distribution in the evaluation of the experimental results, we can arrive at a conclusion regarding the probable value of the measured quantity. Let us assume that a given quantity is measured N times under constant conditions with identical instruments and that the following series of values for this quantity has been obtained:

$$l_1, l_2, \ldots, l_N.$$

What will the probable value of the measured quantity equal? Let it be equal to L. Then the errors are equal to

$$\varepsilon_1 = l_1 - L,$$
$$\varepsilon_N = l_N - L.$$

The probability of the concurrent appearance of quantities ε_1, ε_2, ..., ε_N, as can be seen from the theorem proved earlier and the

- 30 -

Gaussian distribution, is proportional to

$$\left(\frac{1}{h\sqrt{\pi}}\right)^N e^{-\frac{1}{h^2}(\epsilon_1^2 + \epsilon_2^2 + \ldots + \epsilon_N^2)}$$

In this case the probability will attain its maximum when the value of the sum $\sum_1^N \epsilon_i^2$ is at its minimum. This sum can be presented in the following form:

$$\sum_1^N \epsilon_i^2 = V = (l_1 - L)^2 + (l_2 - L)^2 + \ldots + (l_N - L)^2$$

and it is possible to find the condition for its minimum magnitude

$$\frac{dV}{dz} = 2\left[(l_1 - L) + (l_2 - L) + \ldots + (l_N - L)\right] = 0,$$

whence

$$z = \frac{l_1 + l_2 + \ldots + l_N}{N}. \tag{35}$$

This means that if N measurements have been carried out, the most probable (true) value of the sought quantity will be the arithmetic mean of this series of measurements.

It is interesting to note that investigators intuitively employed the law of the arithmetic mean long before the advent of the Gaussian distribution.

Evaluation of direct-measurement results

This section presents the sequence and the formulas (without conclusions) for the evaluation of the direct-measurement results by means of the method of least squares. Generally, the true magnitude (regardless of the number of measurements) is assumed to be the arithmetic mean of the results of N measurements, determined in accordance with Formula (35). It should be pointed out that the quantities l_1, l_2, etc., from which systematic errors and "misses" have already been eliminated, are substituted into this formula. The errors and "misses"

are easily found in an examination of the experimental results.

If $N \geq 10$, the accuracy of the measurements is also evaluated. The residual errors are first evaluated in accordance with the following formula:

$$v_i = l_i - L \tag{36}$$

and the mean square error of the measurement result is evaluated in terms of the following expression:

$$\sigma = \sqrt{\frac{v_1^2 + v_2^2 + \ldots + v_N^2}{N(N-1)}}. \tag{37}$$

Subsequently, the greatest possible error of the measurement result is calculated:

$$\Delta_{max} = 3\sigma \tag{38}$$

and then the probable error of the measurement result is calculated:

$$\rho = 0{,}6745\,\sigma. \tag{39}$$

The quantity ρ divides the error region into two equal parts, i.e., 0.5N lies within the interval $\pm\rho$. The final result of the measurements is written as follows:

$$L_p = L \pm \rho. \tag{40}$$

Evaluation of indirect-measurement results

During tests of engines and their elements many quantities are determined indirectly by means of calculations based on direct-measurement data. Thus, for example, the shaft power of a turboprop engine is calculated from the following formula:

$$N_s = \frac{M_{kp}\,n}{716{,}2} \quad \text{hp},$$

where M_{kr} is the torque; $\underline{n}$ stands for the number of propeller-shaft revolutions.

The quantities M_{kr} and $\underline{n}$ are measured directly during the tests. Thus the power of the engine is determined indirectly on the basis

of direct-measurement results. The most reliable value of N_e is obtained if the quantities M_{kr} and $\underline{n}$ are assumed to be the arithmetic means of the measurement series for the purposes of the calculation.

The evaluation of the indirect-measurement results is carried out in the following manner.

We must find the quantity

$$P = f(x, y, z)$$

in accordance with results obtained in the direct measurement of $\underline{x}$, $\underline{y}$, and $\underline{z}$. The quantities $\underline{x}$, $\underline{y}$, and $\underline{z}$ are defined as the arithmetic means of the measurement series. To determine the relative error of the indirect measurement of the quantity Γ, we use the following formula:

$$\bar{\rho} = \frac{1}{P} \sqrt{\left(\frac{\partial P}{\partial x}\right)^2 \xi_x^2 + \left(\frac{\partial P}{\partial y}\right)^2 \xi_y^2 + \left(\frac{\partial P}{\partial z}\right)^2 \xi_z^2}, \qquad (41)$$

in which $\partial P/\partial x$, $\partial P/\partial y$, and $\partial P/\partial z$ are the partial derivatives of the function P with respect to the arguments $\underline{x}$, $\underline{y}$, and $\underline{z}$; ξ_x, ξ_y, and ξ_z are the absolute errors in the results of the direct measurements of the quantities $\underline{x}$, $\underline{y}$, and $\underline{z}$.

Example. Find the power transmitted by the propeller of a TVD [turboprop engine] if we know that the torque $M_{kr} = 3581 \pm 36$ kg-m and the number of shaft revolutions $n = 1000 \pm 10$ rpm.

The magnitude of the power transmitted by the propellers is calculated in accordance with the following formula:

$$N_e = \frac{M_{kp} n}{716.2}.$$

To determine the relative probable error let us find the partial derivatives

$$\frac{\partial N_e}{\partial n} = \frac{M_{kp}}{716.2}; \qquad \frac{\partial N_e}{\partial M_{kp}} = \frac{n}{716.2}.$$

Then, multiplying the partial derivatives by the probable absolute errors Δn and ΔM_{kr}, and substituting the numerical values of $\underline{n}$ and M_{kr},

we can use Formula (41) to find the probable relative error

$$\bar{p}=\frac{1}{N_e}\sqrt{\left(\frac{\partial N_e}{\partial n}\right)^2\Delta n^2+\left(\frac{\partial N_e}{\partial M_{\kappa p}}\right)^2\Delta M_k^2}=$$

$$=\frac{716,2}{M_{\kappa p}n}\sqrt{\left(\frac{M_{\kappa p}}{716,2}\right)^2\Delta n^2+\left(\frac{n}{716,2}\right)^2\Delta M_{\kappa p}^2}=$$

$$=\sqrt{\left(\frac{\Delta n}{n}\right)^2+\left(\frac{\Delta M_{\kappa p}}{M_{\kappa p}}\right)^2}=\sqrt{\left(\frac{10}{1000}\right)^2+\left(\frac{36}{3581}\right)^2}=0,014.$$

Thus the probable relative error of the indirect-measurement result amounts to 1.4%.

The quantity

$$N_e=\frac{M_{\kappa p}n}{716,2}=\frac{3581\cdot1000}{716,2}=5000\ \text{hp.}$$

The absolute probable error

$$p=pN_e=5000\cdot0,014=70\ \text{hp.}$$

The final result must be written as follows:

$$N_e=5000\pm70\ \text{hp.}$$

Chapter 3

MEASUREMENT INSTRUMENTS AND DEVICES

In this chapter we will examine the methods of measuring parameters characterizing the work of a VRD [ramjet engine] and the descriptions of instruments and measuring devices widely used in laboratory and test-station practice.

Other methods and instruments providing either for increased measuring precision or the measurement of quantities not determined as part of the factory tests are finding ever-greater application in the practice of scientific investigations. For example, optical methods of investigation and measurement are employed in the study of flows, i.e., shadow, interferometer, and spectral-absorption methods. A method involving tracing by means of ions, glowing particles, and electric sparks has found application in the measurement of flow speeds. Methods involving the turning of spectral lines, pyrometric and similar methods, etc., are used in the measurement of high temperatures. The methods of direct and schlieren-photography and interferometry have gained considerable development in the techniques of investigating combustion.

The reader can find a review of the scientific investigatory methods in the special literature.*

1. MEASUREMENT OF PRESSURE

The following pressures are measured during tests of air-reaction engines, i.e., barometric pressure is measured by means of barometers; expansion is measured by means of vacuum gauges; excess pressure over

and above the ambient medium, by means of manometers; and pressure differences by means of differential manometers. In actual practice, however, all instruments for the measurement of pressures or their differences are generally referred to as manometers. The liquid, spring, and piston manometers have gained the greatest acceptance for the measurement of constant or slowly changing pressures.

The idea behind the liquid manometer, in which the pressure or the pressure difference is measured by a column of liquid, was first proposed in 1640 by E. Torichelli [Torricelli]. Spring manometers were developed considerably later by R. Shints [sic] (1846) and Ye. Burdon [Bourdon] (1848). The first membrane manometer was designed by V. Vaydl [sic] in 1847.

Liquid manometers

Three types of liquid manometers gained extensive acceptance, i.e., the U-shaped manometers, the single-tube (cup) manometers, and the micromanometers. A diagram of a U-shaped manometer is shown in Fig. 8.
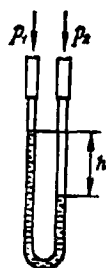
Fig. 8.
Diagram of
U-shaped
manometer.

Let us examine the operation of a manometer. A liquid is poured into two glass tubes that are connected to one another at the bottom. Pressures p_1 and p_2 are applied to the free ends of the tubes. The weight of the liquid column h balances the pressure difference

$$p_2 - p_1 = \gamma h, \qquad (42)$$

where γ is the specific weight of the liquid; and h is the measured pressure difference.

For an exact determination of the value of the difference $p_2 - p_1$ it is necessary to introduce a correction factor for the influence exerted by the temperature of the surrounding medium on the length of the scale, on the specific weight of the liquid, and on the capillarity.

- 36 -

A change in the dimensions of the glass tube exerts no influence on the magnitude of $\underline{h}$.

The true difference may be determined from the measured difference $\underline{h}$ by means of the following formula:

$$h_{\text{и}} = \frac{1 + a(t - t_0)}{1 + b(t - t_0)} h, \qquad (43)$$

where α is the coefficient of linear expansion for the material of the scale; δ is the coefficient of volumetric expansion for the liquid; $\underline{t}$ is the temperature of the ambient medium at the instant of measurement; t_0 is the standard temperature, at which h_d and $\underline{h}$ coincide ($t_0 = 20^{\circ}C$).

The value of α for brass is $0.16 \cdot 10^{-6}$ 1/deg; for glass the corresponding figure is $0.08 \cdot 10^{-6}$ 1/deg; and for steel the figure is $0.11 \cdot 10^{-6}$ 1/deg.

The properties of the most frequently used liquids in manometers are presented in Table 1 on page 38.

Note should be taken of the fact that the tubes of which U-shaped manometers are made generally exhibit a varying inside diameter. This can result in error because of the variation in surface tension at the elbows of the tubes. However, calculations have demonstrated that these errors are not great. Manometers with calibrated tubes are therefore used only for extremely exact measurements.

The correction factors for capillarity are functions of the diameter dimensions of the tube and are calculated according to the following formulas:

for water

$$\Delta h_{\text{к}} = -\left(\frac{32.26}{d} - \frac{1}{6}d\right) \text{ mm}, \qquad (44)$$

for alcohol

$$\Delta h_{\text{к}} = -\left(\frac{12.90}{d} - \frac{1}{6}d\right) \text{ mm}, \qquad (45)$$

TABLE 1

Properties of Working Liquids

1 Наименование рабочей жидкости	2 Химическая формула	3 Удельный вес при 20° С $Г/см^3$	4 Коэффициент объемного расширения при температуре 20° С
5 Ртуть	Hg	13,547	$18 \cdot 10^{-5}$
6 Вода	H_2O	0,998	$21 \cdot 10^{-5}$
7 Керосин	—	~0,800	~$95 \cdot 10^{-5}$
8 Спирт этиловый (96%)	C_2H_5OH	0,790	$110 \cdot 10^{-5}$
9 Четыреххлористый угле- род	CCl_4	1,580	$124 \cdot 10^{-5}$

1) Working liquids; 2) chemical formula; 3) spe-
cific weight at 20°C, g/cm^3; 4) coefficient of
volumetric expansion at a temperature of 20°C;
5) mercury; 6) water; 7) kerosene; 8) ethyl al-
cohol (96%); 9) carbon tetrachloride.
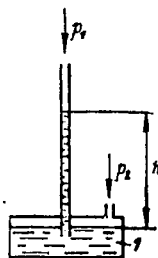
Fig. 9. Dia-
gram of sin-
gle-tube
manometer. 1)
Liquid reser-
voir.
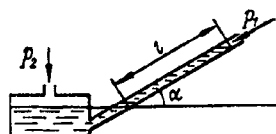
Fig. 10. Diagram of
micromanometer [a
tilting manometer].
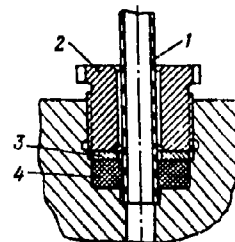
Fig. 11. Joining
of glass tube to
connection pipe.
1) Tube; 2) flare
nut; 3) clamp
ring; 4) packing.

for mercury

$$\Delta h_\kappa = +\left(\frac{6.45}{d} - \frac{1}{6}d\right) \text{ mm,} \tag{46}$$

where $\underline{d}$ is the tube diameter, in mm.

A significant shortcoming in U-shaped manometers involves the
necessity of establishing the level of the liquid simultaneously in
two tubes. A single-tube manometer, a diagram of which is presented in
Fig. 9, avoids this drawback. The measured difference

$$h\gamma = p_2 - p_1.$$

The level of the liquid in the reservoir drops as the measurement is being carried out, while the level in the tube rises. In order to be in a position to neglect the drop in the level in the reservoir and to measure $h \leq 1000$ mm Hg accurate to 0.1%, we provide that the ratio between the diameter of the reservoir and the inside diameter of the tube must not be smaller than 32.

When using single-tube manometers it is necessary, in the majority of cases, to introduce a correction factor for capillarity. Thus, for example, if $p_2 - p_1 = 100$ kg/m^2 or, what is the same, 100 mm of water column, in the case of a tube diameter $d = 4$ mm the rise in the water level in the tube will be 7.4 mm and the measurement error will prove to be equal to 7.4%.

For the measurement of small pressure differences not exceeding 200 mm water column, micromanometers with an inclined tube (Fig. 10) are employed. It is clear that

$$p_2 - p_1 = \gamma l \sin \alpha \qquad (47)$$

(it is assumed that the correction factor for the quantity l has been introduced).

The maximum pressure values should be restricted when using manometers out of considerations of tube strength. Table 2 presents the limit pressure values at which glass tubes are destroyed.

Figure 11 shows one of the methods of strengthening tubes. This type of joint gives good service to 25 kg/cm^2.

The utilization of liquid manometers for the measurement of small pressure differences (below 0.1 kg/cm^2) is fully justified, since water, alcohol, and kerosene can be used as the working liquid.

The measurement of great pressure differences by means of a liquid manometer is quite undesirable, since in order to reduce the dimen-

- 39 -

TABLE 2

Magnitude of Limit Pressure in kg/cm^2 for Glass Tubes

1) Толщина стенки мм	2) Внутренний диаметр трубки в мм						
	1	2	3	4	5	6	7
1	—	310	280	230	220	150	140
2	570	—	340	—	330	240	220
3	560	460	420	400	—	—	230
4	—	450	—	400	310	320	280

1) Wall thickness, in mm; 2) inside tube diameter, in mm.

sions of these manometers mercury is generally employed. Mercury vapors are harmful and on occasion lead to the serious poisoning of the servicing personnel.

Spring manometers

There are three types of spring manometers, i.e., the Bourdon-tube gauge, a diaphragm gauge, and the bellows gauge.

Figure 12 shows a diagram of a spring-type Bourdon-tube gauge. Spring 1 is a flattened [oval shape] tube on the inside of which the measured pressure is applied through connection tube 5. Upon application of the pressure the oval cross section seeks to change into a round cross section which causes spring 1 to straighten and rotate the geared sector 3, which is engaged with hairspring 4, by means of link 2. A pointer is seated on the hairspring shaft. The hairspring is used to eliminate clearances and to provide the required tension.

Fig. 12. Diagram of [Bourdon]-tube manometer [gauge]. 1) Spring; 2) link; 3) sector; 4) gear [hairspring]; 5) connection tube. A) Tube cross section.

Phosphor bronze, brass, and stainless steel are used for the fabrication of the tubes. The phosphor bronze tubes are the most suitable since

- 40 -
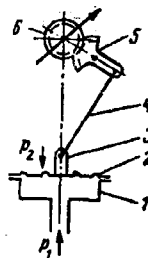
Fig. 13. Diagram of membrane manometer [diaphragm gauge]. 1) Case; 2) diaphragm; 3) stand; 4) link; 5) sector; 6) hairspring.
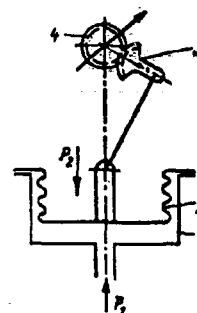
Fig. 14. Diagram of bellows manometer [gauge]. 1) Case; 2) bellows; 3) sector; 4) hairspring.

this material is rather strong under ordinary conditions and is stable to corrosion and also lends itself well to machining.

Steel tubes are used for the measurement of high or markedly changing pressures. Stainless-steel tubes are used for pressure measurements in aggressive media.

For example, for the fabrication of acetylene-manometer tubes it is impossible to use a material containing more than 70% of copper, since in this case an explosive compound is formed, i.e., cuprous acetylide.

Manometer tubes intended for the measurement of hydrogen pressure are made of hydrogen-resistant steel containing carbides with alloying elements.

In the case of manometers intended for the measurement of oxygen, acetylene, etc., pressures, the words "oxygen," "acetylene," etc., are marked on the scale.

Moreover, a manometer employed for the measurement of acetylene

- 41 -

pressure is painted white, while that for the measurement of oxygen is given a light-blue color; a manometer to measure the pressure of hydrogen is painted dark-green, and a yellow color indicates a manometer used for the measurement of ammonia pressure.

Diaphragm gauges (Fig. 13) have also gained widespread acceptance. A pressure p_1 is applied to casing 1 closed off by means of a corrugated diaphragm 2 (flat diaphragms can also be used). The diaphragm is bent and a transmission consisting of stand 3, link 4, sector 5, and hairspring 6, turns the pointer.

An advantage of such manometers lies in their low sensitivity to shaking and they are also rather simple to manufacture; their elevated sensitivity to changes in the temperature of the surrounding medium represents a shortcoming. Diaphragm gauges are used to measure pressures in the range from 0.2 to 30 kg/cm^2.

Bellows gauges are used to measure small pressure differences (Fig. 14). A pressure p_1 is applied to case 1 and this compresses bellows 2. The deformation of the bellows is transmitted to the hairspring. The pointer seated on a common shaft with the hairspring indicates the value of the measured quantity. Bellows gauges are used to measure comparatively small differences ranging from 0 to 5 kg/cm^2.

Electrical remote-control manometers have gained widespread acceptance on aircraft and at testing stations. These are conventional spring (diaphragm) manometers with long-range electrical transmission of the readings. Figure 15 shows the circuit of such an electrical long-range manometer, used for the measurement of fuel and oil pressures.

The manometer receives power from a DC net having a voltage of 27 ± 2.7 v. The manometer receiver is mounted on the engine, while the indicator is situated on an instrument panel; they are wire connected.

- 42 -
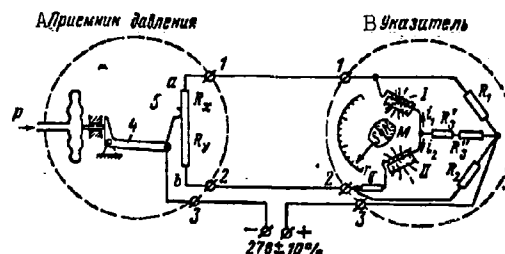
Fig. 15. Schematic diagram of electrical long-range manometer. 1, 2, 3) Long-range transmission and grid contacts; 4) lever; 5) wiper; ab)rheostat; R_x, R_y) variable rheostat resistances; R_1, R_2) constant resistances; r_g) tuning resistance; I, II) frames; R'_3, R''_3) compensating resistances. A) Pressure receiver; B) indicator.

The quantity being measured is transmitted to the diaphragm box. The deformation of the box is transmitted by lever 4 to which a wiper 5 is attached, the latter sliding over the rheostat ab. The rheostat ab and the wiper are connected to the bridge circuit of a ratiometer. With change in the resistances R_x and R_y (as a result of the movement of wiper 5) the currents i_1 and i_2 change, this resulting in a change in the magnetic flux in frames I and II and the turning of the pointer connected to the magnet M.

The constant resistances R_1 and R_2 and the tuning resistance r_g are connected to the ratiometer circuit. The materials of the compensating resistances [cells] R'_3 and R''_3 are chosen so that the temperature of the medium has no effect on the functioning of the instrument.

The advantage of an electrical telemetry [long-range] manometer lies in the fact that no pressure-transmitting tubes are included in its design. The latter would complicate the installation and break as a result of vibration.

Figure 16 shows a kinematic diagram of the sensing element used

- 43 -
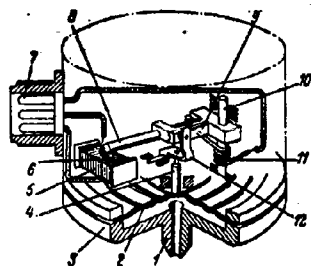
Fig. 16. Kinematic dia-
gram of sensing element
in electrical long-
range manometer. 1) Con-
nection tube; 2) dia-
phragm; 3) base; 4) rod;
5) rheostat; 6) wiper;
7) plug-type connector;
8) wiper rod; 9) link;
10) shaft; 11) spring;
12) rocker.
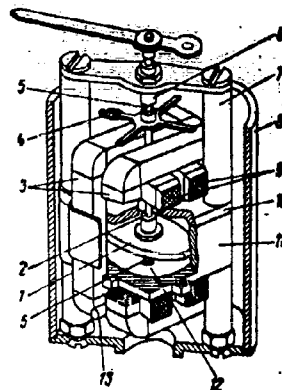
Fig. 17. Kinematic dia-
gram of a ratiometer.
1 and 13) Magnets; 2)
shaft; 3) large frames;
4) balancing weights;
5) cores; 6) adjust-
ment screw; 7) supports;
8) casing; 9) small
frames; 10) cover of
damper; 11) damper; 12)
bearing.

in an electrical telemetry manometer. The pressure being measured is
applied to the sensing element through connection pipe 1 and is picked
up by diaphragm 2. The deformation of the diaphragm is transmitted by
means of rod 4 of rocker 12 to link 9 onto which wiper 6 is fastened.
Wiper 6 moves along rheostat 5 resulting in a change in resistance.

The manometer indicator is the ratiometer whose kinematic diagram
is shown in Fig. 17. The frames are fixed in this ratiometer, while
the magnet is movable. Magnet 1 is made of an alnico alloy and is
fastened to shaft 2. The steel shaft 2 terminates in cores 5 resting
on a bearing and a jewel foot bearing 12. The movable magnet is sur-
rounded by a copper damper 11 in which the magnet, in the case of vib-
rations, excites resistance moments due to eddy currents.

Two pairs of frames 9 and 3, positioned at 90° angles to one an-
other, are placed on the damper. The permanent magnet 13 serves to re-

turn the flexible system to the null position (upon application of current). The parts of the pointer are fastened to frame 8 by means of supports 7 passing through openings in the damper. The frame, made of permalloy, closes the magnetic field of the instrument.

The group recording manometer — GRM-2 — used to measure pressure, expansion, or pressure differences simultaneously at 20 points has gained acceptance in recent years in laboratories and at testing stations; the permissible error of the recording unit is $\pm 0.5\%$ of the limit value of the magnitude being measured by the corresponding sensing element.

The limits of pressure measurement by means of a manometer may vary depending on the stiffness of the sensing elements — the bellows. As a rule, two measurement ranges are tolerated in a single instrument.

The maximum measurement limits for a vacuum gauge range from -1 to 0 kg/cm^2; for a vacuum manometer the limits range from -1 to $+19$ kg/cm^2; and the range for a manometer is 0 to 20 kg/cm^2.

The measurement is carried out by means of automatic spring elements constructed in the form of scales. The measured quantity, depending on the type involved, is applied to a single (in the case of pressure or vacuum measurements) or to two (in the case of the measurement of a pressure difference) bellows which convert the pressure or the vacuum into a force acting on a lever. This force is automatically balanced by the deformation force of the spiral measuring spring. The magnitude of deformation of the measuring spring serves as a measure of the pressure being determined. The instrument consists of twenty identical automatic spring elements consolidated by a common drive and a number of common mechanisms.

All measurement elements of the instruments are mounted on a common frame, and they are wired into two groups for the sake of con-
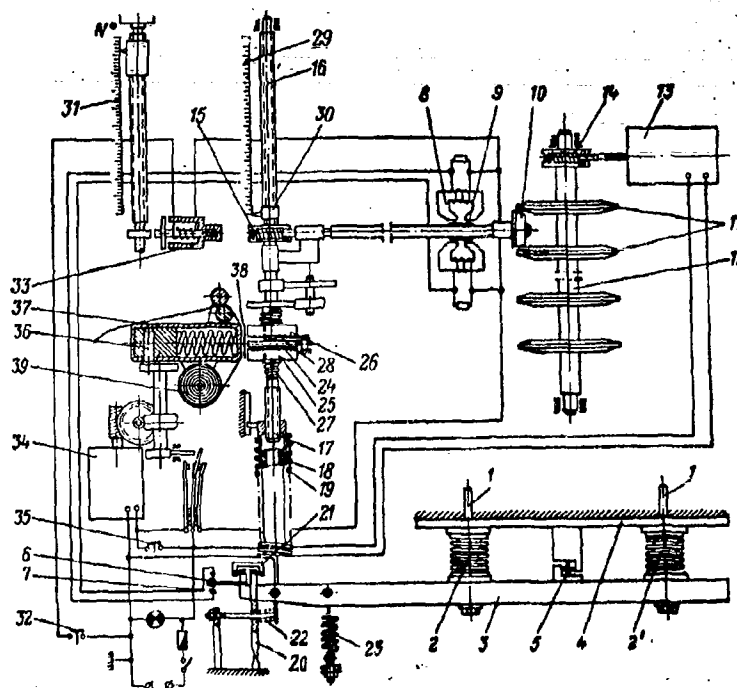
Fig. 18. Diagram of group recording manometer. 1, 1')
Supply tubes; 2, 2') bellows; 3) lever; 4) fixed strip;
5) flexible hinge; 6, 7) contacts; 8) electromagnet; 9)
plate; 10) roller; 11) friction disks; 12) group shaft;
13) electric motor; 14, 15) worm reduction gears; 16)
shaft of direct-reading screw; 17) screw; 18) nut; 19)
measurement spring; 20) lever with plate spring; 21)
connecting rod; 22, 23) springs; 24) pointer; 25, 26)
type wheels;   27) spring; 28) reduction gear; 29) di-
rect-reading scale; 30) pointer; 31) instrument scale;
32) reset key for conventional number; 33) electromag-
net; 34) electric motor; 35) start button of print
mechanism; 36) crank; 37) carriage; 38) ribbon; 39)
paper.

venient utilization, ten measuring elements and a single conventional-
number recording mechanism in each group.

Let us examine the operation of the GRM-2 measuring element (Fig.
18). The pressure to be measured is transmitted through tube 1 to bel-
lows 2 mounted between the fixed strip 4 and lever 3. The lever may
rotate about flexible hinge 5 as a result of bellows deformation. Two

- 46 -

bellows are included in the instrument for purposes of measuring pressure differences.

Bellows 2 expands under pressure and causes lever 3 to shift. There are two movable contacts 6 at the end of lever 3, these contacts positioned between two fixed contacts 7. When lever 3 is in equilibrium, the contacts are open. With reduction or increase in the measured pressure the lever deflects from the equilibrium position, closing one or another pair of contacts, thus actuating one of the two electromagnets 8. The electromagnet attracts plate 9 fastened to the frame of the roller shaft 10 which then engages frictionally with one of the continuously rotating disks 11 of group shaft 12. The direction of roller rotation depends on the disk with which it is engaged, and this in turn depends on which of the two electromagnets has been actuated. The group shaft is brought into rotation by motor 13 through worm gear 14.

Roller 10 through worm gear 15 rotates the shaft of the direct-reading screw 16 and screw 17. As screw 17 turns nut 18 shifts along the screw, altering the tension of measuring spring 19 until lever 3 is in equilibrium, while contacts 6 and 7 remain closed and electromagnet 8 is shut off.

The greater the pressure difference across the bellows, the greater the balancing force must be and the greater the number of revolutions the screw will complete prior to lever equilibrium. The number of screw turns is proportional to the pressure difference across the bellows and serves as a measure of this pressure difference. Thus when the instrument is being used lever 3 is constantly maintained in equilibrium. To raise the sensitivity of the instrument lever 3 is provided with a stiffness compensator consisting of lever 20, connecting rod 21 with flexible hinges, and springs 22 the tension of which can

- 47 -

be regulated. The force of spring 22 is transmitted to the measurement lever through the connecting rod and the flexible hinges.

When the lever is in its equilibrium position this force is directed through the pivotal point and equilibrium is therefore not disrupted. When lever 3 is deflected the position of connecting rod 21 changes and as a result the direction of the force does not coincide with the pivot axis. The resultant moment is applied to lever 3 and acts in the direction of its deflection. The magnitude of the moment is proportional to the angle of lever deflection. The tensile force of spring 22 is set so that the moment from the stiffness compensator, resulting from the deflection of the lever, balances the total moment of all elastic couplings.

The existence of a stiffness compensator raises the sensitivity of the instrument, since very little force is needed to shift the lever from its equilibrium position to the point of closing the contacts.

In addition to the measuring spring, lever 3 carries spring 23 which produces the preliminary force on the lever required for the case in which the instrument is used as a vacuum manometer, this spring serving also to adjust the null readings of the instrument.

At the required times the readings of the instrument are recorded by the printing of scale and indicator segments on paper tapes.

The transmission of the readings to the recording scale proceeds from screw 17. Indicator 24 and type rings 25 and 26 with raised [relief] scales sit freely on the shaft of the screw. Wheel 25 which has 50 divisions is held by spring 27 against the lock of screw 17 and therefore rotates together with the latter. Type wheel 26, with 20 divisions, is connected to the screw by means of reduction gear 28. With each turn of the screw the wheel turns through a single division.

- 48 -

When type wheel 25 has completed a revolution, wheel 26 turns a single division. Thus wheel 25 acts as a vernier for wheel 26. Pointer 24 remains stationary during the turning of the screw.

In addition to the scales on the type wheels, the instrument has direct-reading scales 29 with pointers 30 for continuous monitoring of the pressures being measured.

The number of the instrument and the conventional numbers denoting the number of the measurement and the regime, the time of measurement, or some other factor are printed on the paper tape simultaneously with the measured quantities. For this purpose the instrument is equipped with two number-recording mechanisms that have direct-reading scales 31. The reset mechanism for the conventional numbers is actuated by an electric button 32 that closes the circuit of the electromagnets 33.

The readings are recorded by means of a special mechanism which is actuated by the electric motor 34 and started by button 35. Electric motor 34 through the reduction gear actuates the cranks 36 connected to the carriage 37. During a complete turn of the cranks the carriage moves toward the type wheels, presses a printing tape 38 and paper 39 to the wheels, and then rolls these over the wheels; subsequently the carriage backs off and returns to its initial position. As a result the paper is left with an imprint of the scales and indicator.

Methods of applying pressure to the manometers

Copper, rubber, and plastic tubes are generally used to supply pressure from the sensing elements to the manometers. In measuring pressures in excess of 3 kg/cm^2 copper tubes with soldered or sleeve connections should be used. Rubber tubes are connected to manometers by means of standard connections. When a comparatively high excess pressure is being measured, it is recommended that the portion of the rubber tube on the sleeve be fastened with a copper wire (a double
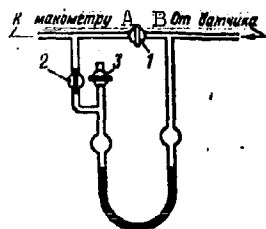
Fig. 19. Diagram of controlling the hermetic sealing of the pressure-measurement system. 1) Check valve; 2) bypass valve; 3) primer. A) To manometer; B) from sensing element.

loop) or that it be held fast by means of a clamp.

Rubber tubes generally adhere to one another when a vacuum is being measured and it is therefore best to use vacuum rubber or copper tubes. If pressure fluctuations occur in the system being investigated, these can be reduced in the transmission to the instrument by the introduction of capillaries and dampers.

It is an absolute necessity that the pressure-measurement systems be checked for air tightness both prior to the experiment and after the completion of same. This check should be carried out with an excess pressure or vacuum greater than during the experiment itself.

Figure 19 shows one of the possible diagrams of maintaining continuous control over the hermetic sealing of a gas-pressure measuring system. Valve 1 should be closed for a check of the system; if there are losses in the system between valve 1 and the manometer, bubbles of gas will begin to pass through the liquid (valve 2 is open, and primer 3 is closed).

In the case of excess pressure the hermetic sealing can be checked by wetting the suspected points with soapy water and observing the behavior of the film.

Measurement accuracy and manometer calibration

In the practice of testing VRD [ramjet engines] liquid manometers are generally not calibrated. Measurement accuracy is determined through the introduction of appropriate correction factors and the magnitude of the pressure difference.

- 50 -
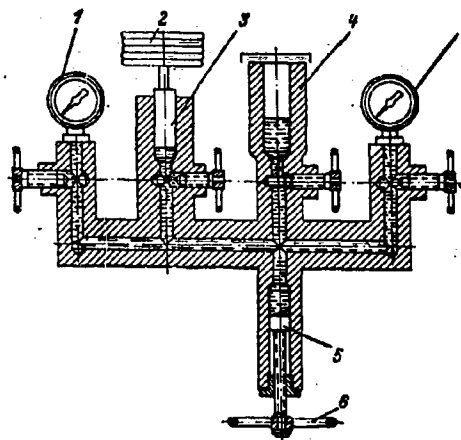
Fig. 20. Diagram of piston manometer. 1) Calibrated manometer; 2) weights; 3) plunger; 4) liquid reservoir [well]; 5) piston; 6) flywheel.

Spring manometers are calibrated by means of control or standard spring and piston manometers. Figure 20 shows the diagram of a piston press for the calibration of spring manometers.

General-purpose (operating) spring manometers are manufactured for five classes of precision: 0.5; 1.0; 1.5; 2.5; and 4. Control manometers are used for exact measurements and the verification of working manometers. They are more precise and are manufactured for two classes of precision, i.e., 0.5 and 1.0.

Standard spring manometers serve for the verification of the control and operating manometers, as well as for laboratory measurements; these types of manometers are manufactured for two classes of precision: 0.20 and 0.35, i.e., the measurement error does not exceed ± 0.20 and $\pm 0.35\%$ of the upper limit at an ambient-medium temperature of $+20 \pm 5^\circ C$.

Standard piston manometers suitable for pressures below 50 kg/cm^2 ensure a measurement accuracy in which the error is not greater than

$\pm 0.01\%$ of the measured pressure, while below 250 kg/cm^2 the error is not greater than $\pm 0.02\%$ of the measured quantity.

A standard piston manometer provides a measurement accuracy with an error not in excess of $\pm 0.02\%$ for pressures below 50 kg/cm^2, while for pressures higher than 50 kg/cm^2 the error does not exceed $\pm 0.05\%$. Standard piston manometers are widely used for the calibration of control and standard spring manometers.

Aircraft manometers yield a measurement error not in excess of $\pm 3\%$.

2. MEASUREMENT OF TEMPERATURES

The "International Practical Temperature Scale of 1948," adopted by the IXth General Conference of Measures and Weights represents a practical temperature scale. This scale is based on the constant and comparatively easily reproduced temperatures of phase equilibrium which are known as reference points.

Subsequent conferences introduced certain changes into the temperature scale.

The Xth General Conference of Measures and Weights (1954) defined the temperature scale in terms of the basic reference point — the triple point of water which corresponds to a temperature of 273.16°K. The triple point of water is the point at which the solid, liquid, and gas phases are in equilibrium; it may be reproduced with an error no greater than 0.0001°C.

The XIth General Conference of Measures and Weights (1960) recommended the temperature of the solidification of zinc (419.505°C) as an additional reference point.

Table 3 shows data on the absolute accuracy and the reproducible accuracy of the practical scale.

It is the convention at present to hold that deviation in the

- 52 -

TABLE 3

Reference Points for the Temperature Scale at a Pressure of 760 mm Hg

1 Реперная точка	t °C	2 Точность осуществления °C	3 Точность воспроизведения °C	4 Измерительный прибор
5 Кипение кислорода	−182,97	±0,02	±0,020	11 Термометр сопротивл.
6 Тройная точка воды (основная реперная точка)	0,01	—	±0,0001	То же 12
7 Кипение воды	100,00	—	±0,003	»
8 Кипение серы	444,60	±0,10	±0,005	13 »
9 Затвердевание серебра	960,8	—	—	Термопара
10 Затвердевание золота	1063,0	±1	±0,050	»

1) Reference point; 2) accuracy of realization, °C; 3) accuracy of reproduction, °C; 4) measuring instrument; 5) boiling of oxygen; 6) triple point of water (basic reference point); 7) boiling of water; 8) boiling of sulfur; 9) solidification point of silver; 10) solidification point of gold; 11) resistance thermometer; 12) the same; 13) thermocouple.

values of the reference points from the absolutely accurate temperature scale does not exceed $\pm 0.02°$ for $-182.97°$, $\pm 0.10°$ for $444.60°C$, etc. (see Table 3).

The problem of reproducing the reference points is incomparably simpler than the task of realizing the exact scale and, as can be seen from Table 3, it is resolved substantially more precisely in the temperature range above $0°C$.

The most precise thermometric projects are carried out with gas thermometers filled with hydrogen and helium. The utilization of these gases for precise measurements of temperature is based on the utilization of the Clapeyron equation with corrections.

In testing VRD [ramjet engines] the following are used:

1) liquid thermometers for the measurement of the temperature of the ambient medium, at the test stand;

2) manometric thermometers for measurement of all temperature (in-
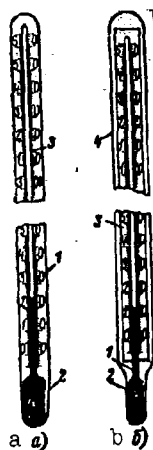
Fig. 21. Thermometers. a) A stem thermometer; 1) a thick-walled capillary; 2) bulb; 3) scale etched into capillary surface; b) thermometer with inserted scale; 1) capillary; 2) bulb; 3) scale plotted on plate of milk glass; 4) protective casing.

frequently);

3) resistance thermometers for the measurement of air temperature in investigating inlets and compressors, oils and fuels;

4) thermocouples for the measurement of gas and engine component-part temperatures.

Liquid thermometers

Liquid thermometers are extremely simple and are distinguished by their high measurement accuracy.

The operating principle of a liquid thermometer is based on the thermal expansion of a liquid in glass. It is for this reason that the measurement of temperature by means of these thermometers is reduced to the observation of the change occurring in a visible volume of liquid. In the majority of cases we encounter thermometers of two basic types, i.e., a stem thermometer and a thermometer into which a scale has been inserted (Fig. 21).

Suppose the level of the liquid at $0°C$ is set at the zero marking on the scale. With a change in temperature the volume of the liquid is changed and the glass bulb of the thermometer as well. The visible expansion of the liquid ΔV is equal to the difference between the expansion $\Delta V'$ of the liquid and the expansion $\Delta V''$ of the thermometer. Obviously

$$\Delta V = \Delta V' - \Delta V'',\qquad(48)$$

whence

$$\frac{1}{V_0}\frac{dV}{dt}=\frac{1}{V_0}\frac{dV'}{dt}-\frac{1}{V_0}\frac{dV''}{dt},\qquad(49)$$

where V_0 is the volume of the liquid at $0^{\circ}C$.

Let us introduce the following concepts: the coefficient of the visible expansion of the liquid

$$a = \frac{1}{V_0} \frac{dV}{dt},$$

the coefficient of liquid expansion

$$a' = \frac{1}{V_0} \frac{dV}{dt},$$

the coefficient of the expansion of glass

$$a'' = \frac{1}{V_0} \frac{dV''}{dt},$$

and we derive the following formula:

$$a = a' - a''. \tag{50}$$

Evidently,

$$dl = a \frac{V_0}{f} dt, \tag{51}$$

where dl is the change in the level of the liquid in the capillary; $\underline{f}$ is the cross sectional area of the capillary.

For given a, V_0, and dt the magnitude of dl is all the greater, the smaller $\underline{f}$, i.e., the sensitivity dl/dt of the thermometer is all the greater, the greater the ratio V_0/f.

The properties of liquids used to fill thermometers are presented in Table 4.

Mercury thermometers are used to measure temperatures up to $750^{\circ}C$; in this case the capillary space above the mercury is filled with nitrogen or some similar inert gas exhibiting a pressure of about 70 atm.

Table 5 shows the values of the coefficient of visible expansion of mercury for the various types of glass from which the capillary tubes for thermometers are made.

In the determination of commercially precise temperatures it is desirable to immerse the thermometer into a medium to the initial scale

Properties of Thermometer Liquids at 760 mm Hg

1 Вещество	2 Химическая формула	3 Коэффициент расширения при 18° C	4 Температура в °C			
			5 затвердевания		6 кипения	
			7 от	8 до	7 от	8 до
9 Метиловый спирт	CH$_3$OH	0,001220	—93,9	—97,8	+64,2	+66,0
10 Этиловый спирт	C$_2$H$_5$OH	0,001100	—111,8	—117,3	+77,7	+78,4
11 Пентан (чистый)	C$_5$H$_{12}$	—	—130,8	—147,5	+36,0	+36,5
12 Толуол	C$_6$H$_5$CH$_3$	0,001090	—92,4	—102	+102	+110,6
13 Ртуть	Hg	0,000181	—38,87	—38,87	+356,7	+356,7

1) Substance; 2) chemical formula; 3) coefficient of expansion at 18°C; 4) temperature, in °C; 5) solidification [melting] point; 6) boiling point; 7) from; 8) to; 9) methyl alcohol; 10) ethyl alcohol; 11) pentane (pure); 12) toluene; 13) mercury.

division. If this is impossible, a correction for the protruding column must be introduced. Figure 22 shows a diagram of the installation of a basic (measuring) thermometer in a tube and that of an auxiliary thermometer for the introduction of a correction factor. The auxiliary thermometer is held to the basic thermometer by means of rubber clamps so that the bulb of the auxiliary thermometer is situated approximately in the middle of the protruding column of the thermometer liquid of the basic thermometer.

In Fig. 22 the O_1 and O_2 indicate the zero settings of the thermometers. It is assumed in the introduction of the correction factors that the t_1 portion of the thermometer and the bulb are at the temperature t_s of the medium, while the upper portion of the thermometer $t_2 - t_1$ is at the temperature t_v (i.e., the temperature shown by the auxiliary thermometer).

The true temperature of the medium is determined from the following formula:

$$t_c = \frac{t_s - \alpha t_v (t_2 - t_1)}{1 - \alpha (t_2 - t_1)}. \tag{52}$$
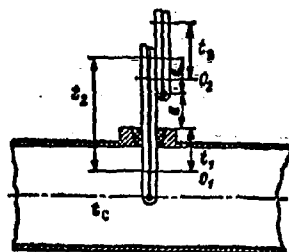
Fig. 22. Diagram showing the set-up of a basic and auxiliary thermometer.

TABLE 5

Values of the Coefficient of the Visible Expansion of Mercury for Various Capillary Materials

1 Сорт стекла	a_0^{100}
2 Термометрический 16^{III}	$1.57 \cdot 10^{-4}$
3 Термометрический 59^{III}	$1.64 \cdot 10^{-4}$
4 Кварц	$1.79 \cdot 10^{-4}$
5 Термометрический ГОСТ 1224—41	$1.58 \cdot 10^{-4}$

1) Glass grade; 2) thermometer, 16^{III}; 3) thermometer, 59^{III}; 4) quartz; 5) thermometer, GOST 1224-41 [All-Union State Standards].

Formula (52) is approximate since α is in actual fact a function of the temperature. However, in the majority of practical cases this formula can be employed if the value of α is taken at a temperature of t_v °C.

Manometric thermometers

Manometric thermometers come in liquid, vapor, and gas versions. A diagram of a manometric thermometer is shown in Fig. 23. The reservoir [bulb] (sensing element of the thermometer) 1 is filled to 60% of capacity with an easily vaporizing liquid (methyl ether, methylchloride, etc.); the capillary tube 2 transmitting the vapor pressure is most frequently filled with the same liquid.

In view of the fact that there is no direct proportionality between the temperature of the bulb and the vapor pressure of the thermometric liquid, the thermometer scale proves to be nonuniform. As a result of a number of shortcomings, i.e., the inadequate strength of the capillary, low accuracy, difficulty in repair, these thermometers have virtually been replaced completely by electrical thermometers.
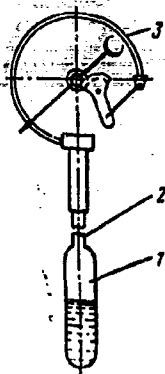
Fig. 23. Diagram of
manometric thermom-
eter. 1) Sensing ele-
ment of thermometer;
2) transmitting tube;
3) temperature indi-
cator (manometer).
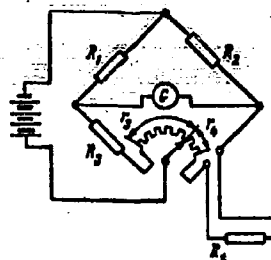
Fig. 24. Schematic
diagram of resist-
ance thermometer
with a balanced
bridge. R_1, R_2, and
R_3) Resistance con-
stants; $r_3 r_4$) bal-
anced resistances;
R_t) resistance of
sensing element.

Resistance thermometers

The operating principle of resistance thermometers is based on
the change in the electrical resistance of certain conductors under
the action of temperature. The sensing element whose resistance changes
as a function of temperature is incorporated in a balanced bridge, a
schematic diagram of which is shown in Fig. 24.

The sensing element of the thermometer is the resistance R_t. With
a change in the temperature the magnitude of the resistance R_t changes
and this disrupts the equilibrium of the bridge which is determined by
the galvanometer G. The instrument scale is calibrated in $^\circ$C. The
power supply for the instrument is provided by a battery or some other
DC source.

Resistance thermometers are made of platinum, copper, nickel,
iron, and special alloys. It should be pointed out that platinum is
capable of preserving its physical properties for long periods of time.
As a result a platinum resistance thermometer is the type employed for

- 58 -

the interpolation of the international temperature scale in the range between —180 and 660°C.

The relationship between the temperature t °C of the medium and the resistance R_t in the range from 0 to 1100°C is established with great accuracy by the following equation:

$$t = 100\frac{R_t - R_0}{R_{100} - R_0} + \delta\left(\frac{t}{100} - 1\right) + \gamma\,\frac{t}{100}\left(\frac{t}{100} - 1\right)\left(\frac{t}{444,6} - 1\right). \quad (53)$$

in which the constants R_0, R_{100}, δ, and γ are determined experimentally on the basis of the reference points. Here R_0 and R_{100} are the resistances for the temperatures 0 and 100°C.

TABLE 6

Temperature Measurement Limits with ETP, ETM, and ETN Resistance Thermometers

1 Материал чувствительного элемента термометра	2 Условное обозначение термометра	3 Приборы измерения температур в °C	
		наименьшая	наибольшая
6 Платина	9 ЭТП	—200	+500
7 Медь	10 ЭТМ	—50	+150
8 Никель	11 ЭТН	—50	+200

1) Material for the sensing element of the thermometer; 2) conventional denotation of thermometer; 3) instruments for the measurement of temperatures, in °C; 4) minimum; 5) maximum; 6) platinum; 7) copper; 8) nickel; 9) ETP; 10) ETM; 11) ETN.

The resistance ratio R_{100}/R_0 can serve as a characteristic of the purity of the platinum; for platinum of the first-class "Ekstra" brand, $R_{100}/R_0 = 1.389 \pm 0.0007$.

The copper used for resistance thermometers exhibits a great thermal coefficient of resistance ($\alpha = 4.25\cdot10^{-3}$-$4.28\cdot10^{-3}$) and makes it possible to determine the thermal resistances R_t according to the fol-

lowing equation:
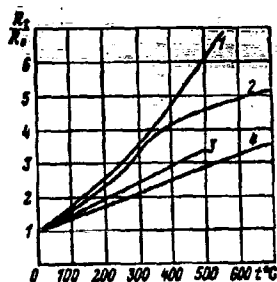
$$R_t = R_0 (1 + \alpha t). \qquad (54)$$

Fig. 25. Change in the resistance of metals as a function of temperature. 1) Iron; 2) nickel; 3) copper; 4) platinum.

A shortcoming of copper is its low specific resistance ($\rho = 0.017$ ohm·mm^2/m) and its oxidizability which restricts the area of its application below temperatures of 150°C.

Nickel exhibits a high thermal coefficient ($\alpha = 6.21 \cdot 10^{-3} - 6.34 \cdot 10^{-3}$). However, nickel exhibits a complex relationship between the thermal coefficient and the temperature, which is a significant shortcoming.

Resistance thermometers and the temperature-measurement limits of same have been standardized (GOST 6651-59) and are presented in Table 6.

Figure 25 shows the change in the ratio of the resistance R_t and the resistance R_0 as a function of temperature for a number of metals.
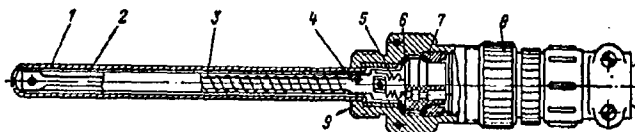
Fig. 26. Resistance thermometer receiver. 1) Protective tube; 2) insulation; 3) heat-sensing element; 4) mica plate; 5) extra resistance; 6 and 7) inserts; 8) plug-type connector; 9) connection tube.

The design of the resistance-thermometer receiver is shown in Fig. 26. The protective tube 1 is made of stainless steel, the heat-sensing element 3 is made of a nickel wire 0.05 mm in diameter, this wire being wound about a mica plate 4.

Aviation resistance thermometers operate from a DC source with a voltage of 27 ± 2.7 v.

Thermoelectric thermometers

The principle of measuring temperatures by means of thermoelectric thermometers is based on the phenomenon of thermoelectricity discovered in 1758 by the Russian academician F. Epinus. This phenomenon is explained by the fact that all metals consist of positively charged stationary ions and free negatively charged electrons which can be compared to the free gas which fills the intermolecular space.

The density and pressure of the electron gas differs in various metals at any given temperature. If two wires A (a copper wire) and B (a platinum wire) are welded or soldered, as shown in Fig. 27, the electrons from the copper wire will begin to transfer to the platinum wire. Close to junctions 1 and 2 the copper wire will be positively charged, while the platinum wire is negatively charged. The electric fields originating at junctions 1 and 2 counteract the transfer of electrons from one material to the other and at some potential difference the process of the electron transfer is curtailed, since dynamic equilibrium sets in, i.e., the quantity of electrons leaving a given material becomes equal to the quantity of electrons entering the material.

Fig. 27.
Thermoelectric circuit.

If junction 1 is heated to temperature t, and the temperature t_0 of junction 2 remains constant $(t_0 < t)$, a current appears in the circuit consisting of conductors A and B, i.e., the circuit will become a generator of electric energy. The conductors in the circuit under consideration are known as thermoelectrodes, and the junctions are known as thermojunctions.

As has been demonstrated in numerous experiments, the following equation is valid for a thermoelectric circuit:
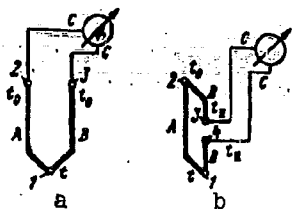
Fig. 28. Diagram for
the incorporation of
the measurement in-
strument into the
thermoelectric circuit.

$$E_{AB}(t, t_0) = e_{AB}(t) + e_{BA}(t_0), \quad (55)$$

where $E_{AB}(t, t_0)$ is the thermoelectromotive
force in the circuit, the direction of the
current from A toward B; $e_{AB}(t)$ is the
thermoelectromotive force at junction 1;
$e_{BA}(t_0)$ is the thermoelectromotive force at
junction 2, with the direction of the cur-
rent from B toward A.

Given the equality of the temperatures at the two junctions, the
thermoelectromotive force of the circuit is equal to zero, i.e., if

$$t = t_0,$$

then

$$E_{AB}(t, t_0) = 0.$$

In this case

$$e_{BA}(t_0) = -e_{AB}(t_0)$$

and, consequently, Eq. (55) can be written as follows:

$$E_{AB}(t, t_0) = e_{AB}(t) - e_{AB}(t_0). \quad (56)$$

Equation (56) makes it possible to determine the temperature t if
the thermoelectromotive force of the circuit and the temperature t_0
are known, i.e., the latter referring to the temperature of the cold
junction. The quantity $E_{AB}(t, t_0)$ can be measured by means of a pyro-
metric millivoltmeter or potentiometer. The temperature t_0 of the cold
junction should be kept constant and rigorously defined during the
measurement process. Best of all, junction 2 should be placed in a
medium exhibiting a temperature $t_{sr} = t_0 = 0^{\circ}C$, e.g., in water with
melting ice.

The materials of the thermoelectrodes should be selected so that
the quantity $E_{AB}(t, t_0)$ is as great as possible.

Thus the measurement of the temperature t is, in principle, pos-

sible with the aid of the thermoelectric circuit (thermocouple) shown in Fig. 27.

The galvanometer used to measure the thermoelectromotive force in the circuit can be connected in one of two ways (Fig. 28). In the first circuit the galvanometer is connected between the cold junctions 2 and 3, junction 1 in this case being hot (see Fig. 28a).

In the second circuit the galvanometer is connected to the split electrode B and junction 1 in the circuit will be hot, junction 2 will be cold, and junctions 3 and 4 will be neutral (see Fig. 28b).

In determining temperatures it is the practice to hold that the temperatures of the cold junctions 2 and 3 (see Fig. 28a) and the neutral junctions 3 and 4 (see Fig. 28b) in the circuit are identical. The thermoelectromotive forces of the various circuits will be equal if the total resistance of the corresponding wires and electrodes and the temperatures of the cold and hot junctions of these circuits will also be equal.

In actual fact the circuit shown in Fig. 28a consists of three conductors A, B, and C (the presence of the instrument does not change the validity of the cited conclusion). On the basis of the second law of thermodynamics, given the equality of temperatures $t_0 = t$, the thermoelectromotive force in the circuit is equal to zero. This means that for this case we can write:

$$e_{AB}(t) + e_{BC}(t) + e_{CA}(t) = 0,$$

or

$$e_{BC}(t_0) + e_{CA}(t_0) = -e_{AB}(t_0). \qquad (57)$$

If junction 1 will exhibit a temperature $\underline{t}$, and junctions 2 and 3 will exhibit temperatures of t_0,

$$E_{AB}(t, t_0) = e_{AB}(t) + e_{BC}(t_0) + e_{CA}(t_0). \qquad (58)$$

Substituting the value of the sum $e_{BC}(t_0) + e_{CA}(t_0)$ from Formula

(57) into Formula (58) we will obtain

$$E_{AB}(t, t_0) = e_{AB}(t) - e_{AB}(t_0). \tag{59}$$

As we can see Formulas (56) and (59) are identical; it is therefore possible to maintain that the thermoelectromotive force developed by the circuit shown in Fig. 28a and that developed by the initial circuit (Fig. 27) are equal.

The following equality is valid for the circuit shown in Fig. 28b:

$$E_{AB}(t, t_0) = e_{AB}(t) + e_{BC}(t_\mathrm{R}) + e_{CB}(t_\mathrm{R}) + e_{BA}(t_0). \tag{60}$$

Taking into consideration the equalities

$$e_{BC}(t_\mathrm{R}) = -e_{CB}(t_\mathrm{R}) \tag{61a}$$

and

$$e_{BA}(t_0) = -e_{AB}(t_0), \tag{61b}$$

we will obtain

$$E_{AB}(t, t_0) = e_{AB}(t) - e_{AB}(t_0). \tag{62}$$

Thus the circuit shown in Fig. 28b was also equivalent to the initial circuit (see Fig. 27).

It may turn out that the temperature of the cold junction 2 in the circuit in Fig. 28a is equal to t'_0 and that that of junction 3 is equal to t_0. Then

$$E = e_{AB}(t) + e_{BC}(t_0) + e_{CA}(t'_0). \tag{63}$$

Subtracting Eq. (63) from (59), we will obtain

$$E_{AB}(t, t_0) - E = e_{BA}(t_0) + e_{CB}(t_0) + e_{AC}(t'_0). \tag{64}$$

Taking into consideration the following equality

$$e_{AB}(t_0) = e_{AC}(t_0) + e_{CB}(t_0), \tag{65}$$

instead of Eq. (64) we can write

$$E_{AB}(t, t_0) - E = e_{AC}(t'_0) - e_{AC}(t_0). \tag{65}$$

Analogous expressions can be derived for the case of unequal temperatures for the neutral junctions 3 and 4 in the circuit in Fig. 28b.

If the temperature of the cold junction in circuit a or b changes

- 64 -

or becomes equal to t'_0, the thermoelectromotive force will also change and become equal to

$$E_{AB}(t, t'_0) = E_{AB}(t, t_0) - e_{AB}(t'_0) + e_{AB}(t_0). \qquad (66)$$

As we can see Eq. (66) makes it possible to calculate $E_{AB}(t, t_0)$ from the measured quantity $E_{AB}(t, t'_0)$ and the correction factor for the temperature of the cold junction:

$$e_{AB}(t'_0) - e_{AB}(t_0).$$

The thermoelectric circuit set up in the manner shown in Fig. 28b can be used to measure temperature differences.

In this case junctions 1 and 2 are hot junctions and it is precisely their temperature difference that is being determined. Junctions 3 and 4 become cold and their temperatures must be identical (its magnitude is of no significance).

The magnitude of the correction factor for the temperature of the cold junction is determined from the calibration graph for the thermo-couple (Fig. 29).

Let there be three materials A, B, and C. Let us make three thermocouples AB, AC, BC out of these materials. The following equalities are valid for these thermocouples:

$$E_{AB}(t, t_0) = e_{AB}(t) - e_{AB}(t_0); \qquad (67)$$
$$E_{AC}(t, t_0) = e_{AC}(t) - e_{AC}(t_0); \qquad (68)$$
$$E_{BC}(t, t_0) = e_{BC}(t) - e_{BC}(t_0). \qquad (69)$$

Taking the following equation into consideration

$$e_{AB}(t_0) + e_{BC}(t_0) + e_{CA}(t_0) = 0$$

and carrying out simple transformations, we will obtain

$$E_{BC}(t, t_0) = E_{BA}(t, t_0) - E_{CA}(t, t_0). \qquad (70)$$

This equation will make it possible to handle the calculations for any thermocouples of electrodes B, C, D, etc., if their thermoelectromotive forces are known with respect to electrode A which is desig-

- 65 -
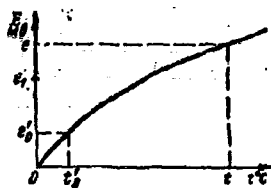
Fig. 29. Introduction of correction factor for cold-junction temperature. e_1) Measured emf; e'_0) magnitude of emf corresponding to correction factor for cold-junction temperature; $e = = e_1 + e'_0$) total emf; t'_0) cold-junction temperature; t) measured temperature.
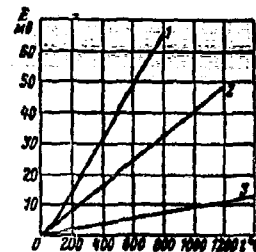

Fig. 30. Thermocouple characteristics. 1) Chromel-copel; 2) chromel-aluminum; 3) platinum-platinorhodium.

TABLE 7

Range of Thermocouple Application

1 Термопара	2 Область применения °C
3 Иридий-иридиеродий	8 до 2000
4 Платина-платинородий	0÷1450
5 Хромель-алюмель	−200÷1200
6 Хромель-копель	−200÷800
7 Медь-константан	−200÷350

1) Thermocouple; 2) range of application, in °C; 3) iridium/iridium-rhodium; 4) platinum/platinorhodium; 5) chromel-alumel; 6) chromel-copel; 7) copper-constantan; 8) below 2000.

nated as normal. Chemically pure platinum is used as the normal thermoelectrode.

The functioning of the thermocouple and the limits of temperature measurement depend to a considerable degree on the materials of the thermoelectrodes; it is therefore extremely important to select these materials properly. The following requirements are imposed on the ma-

terials:

1) the thermoelectromotive force must increase with a rise in temperature (preferably, linearly);

2) the magnitude of the thermoelectromotive force must be sufficiently great;

3) the coefficient of electrical resistance must be at its minimum, while that of electrical conductivity must be high;

4) the physicochemical properties of these materials must not change under conditions of normal operation;

5) the materials must be corrosion resistant;

6) the melting point must be considerably higher than the temperature being measured;

7) the materials of the thermoelectrodes must be rather uniform.

Thermocouples made of metals (noble and base) have gained the greatest acceptance, but for purposes of measuring high temperatures metal thermoelectrodes in combination with nonmetals are sometimes used, e.g., tungsten-graphite.

A list of the most frequently used thermocouples is cited in Table 7.
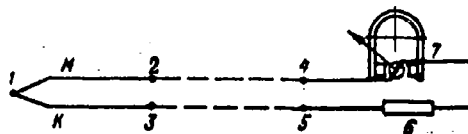

Fig. 31. Diagram of thermoelectric pyrometer. 1) Thermocouple; 2-4, 3-5) connecting wires; 6) additional resistance; 7) galvanometer.

Figure 30 shows the characteristics of some thermocouples used in testing VRD. The construction of the thermocouples is described in the section devoted to flow measurements.

Figure 31 shows a diagram of the thermoelectric pyrometer that is

conventionally used. Thermocouple 1 is connected to the instrument by means of connecting wires 2-4 and 3-5. If the thermocouple is made of inexpensive materials, wires 2-4 and 3-5 may be made of the same materials.

If the thermoelectrodes of thermocouple 1 are made of noble metals, it becomes necessary to have connecting wires that should be made of inexpensive materials exhibiting thermoelectric characteristics close to the thermoelectrode materials. It is always preferable for the temperatures of junctions 2 and 3 to be identical.

Junctions 4 and 5 are cold. They are separated from junctions 2 and 3 by a considerable distance, thus simplifying the maintenance of their temperatures which are equal to one another and constant throughout the course of the experiment. It is best to immerse these junctions into an oil-filled test tube, and the test tube should be placed in a thermostat with melting ice. If there is no ice, the cold junction can be immersed into a vessel with oil (the temperature of which can be regulated), and a correction factor for the temperature of the cold junctions is introduced into the evaluation of the measurement data.

The circuits for the connection of the thermocouples to the instrument by means of a switch are used for the measurement of temperatures at a great number of points. In view of the smallness of the thermocouple current (0.5-1.0 ma) all wires have to be thoroughly insulated. If the scale of the electromeasurement instrument is graduated in degrees, the resistances of all the pyrometers must be identical. The resistances are adjusted by means of the additional resistances 6. A copper wire is used to connect the instrument to junctions 4 and 5.

For purposes of thermocouple design we require data on the materials used for the thermoelectrodes, the connecting wires, and on

TABLE 8

Thermoelectromotive Forces of Metals in Combination with Chemically Pure Platinum at t = 100°C and $t_0 = 0$°C

1 Наименование металлов	2 Обозначение или состав	Температура применения в °C 3		6 Термо-э. д. с. мв
		длитель-ная 4	кратко-временная 5	
7 Алюмель	95% Ni+5% (Al+Si+Mn)	1000	1250	—1,02÷1,38
8 Вольфрам	W	2000	2500	+0,79
9 Железо (химически чистое)	Fe	600	800	+1,80
10 Константан	60% Cu+40% Ni	600	800	—3,50
11 Копель	56% Cu+44% Ni	600	800	—4,00
12 Медь (химически чистая)	Cu	350	500	+0,76
13 Платина „Экстра"	Pt	1300	1600	±0,00
14 Платинородий	90% Pt+10% Rh	1300	1600	+0,64
15 Платиноиридий	90% Pt+10% Ir	1000	1200	+1,30
16 Хромель	90% Ni+10% Cr	1000	1250	+2,7÷+3,13

1) Metals; 2) symbol or composition; 3) application temperature, in °C; 4) prolonged; 5) brief; 6) thermoelectromotive force, in mv; 7) alumel; 8) tungsten; 9) iron (chemically pure); 10) constantan; 11) copel; 12) copper (chemically pure); 13) "Ekstra" platinum; 14) platinorhodium; 15) platinoiridium; 16) chromel.

the resistance of the instrument. Table 8 presents some data for the most widely used materials.

The "+" sign in front of the value of the thermoelectromotive force indicates that the current in the cold junction is directed from the given material to the platinum. Using the data in Table 8 we can determine the thermoelectromotive forces of certain thermocouples and the possibilities for their application.

Example. We must determine the thermoelectromotive force of a chromel-alumel thermocouple at t = 100°C and $t_0 = 0$°C, if in combination with platinum they develop thermoelectromotive forces of

$$E_{Хп}(100°,0°) = +2,70 \text{ mv},$$
$$E_{Ал}(100°,0°) = -1,38 \text{mv}.$$

The thermoelectromotive force of the chromel-alumel thermocouple

will be

$$E_{XA}(100°, 0°) = E_{Xn}(100°, 0°) - E_{An}(100°, 0°) = +2,70 - (-1,38) = = +4,08 \text{ mv}.$$

The "+" sign indicates that the current in the cold junction flows from the chromel to the alumel.

Millivoltmeters and potentiometers are used to measure thermocouple thermoelectromotive forces.

Figure 32 shows a circuit which clarifies the basis of the potentiometric (compensation) method. In this circuit the resistance R is known, while the current source $\underline{B}$ keeps the current I virtually constant throughout the measurement. The slide $\underline{b}$ slides along the rheostat to which the current source A and one clamp of the thermocouple are attached. The null indicator $\underline{NP}$ is connected to point $\underline{a}$ by a single clamp, the other clamp being attached to switch $\underline{P}$ by means of which it is possible to disconnect the thermocouple or the current source A.

In the measurement of thermoelectromotive forces the $\underline{NP}$ instrument is connected into the thermocouple circuit by means of switch $\underline{P}$ and slide $\underline{b}$ changes the resistance of the circuit until the pointer of the $\underline{NP}$ [null indicator] points to zero.

Clearly, in this position

$$E_{\tau} = IR_1.$$

where R_1 is the resistance of the segment ab; E_t is the thermoelectromotive force of the thermocouple.

Then the switch $\underline{P}$ cuts in source A and slide $\underline{b}$ again is used to achieve zero readings on the $\underline{NP}$. For this case

Fig. 32. Schematic circuit diagram of potentiometer. A, $\underline{B}$) Current sources; E_t) thermocouple emf; $\underline{NP}$) null indicator; b) slide; $\underline{P}$) switch.
Б = $\underline{B}$; H = $\underline{N}$; П = $\underline{P}$.

$$E_n = IR_2,$$

where E_n is the emf of the normal element A; R_2 is the new resistance of the segment ab.

Having transformed the derived equalities for E_t and E_n, let us find the value of the thermoelectromotive force of the thermocouple

$$E_t = E_n \frac{R_1}{R_2}. \qquad (71)$$

This method ensures high accuracy in the measurement of temperatures and is used in research work. At the present time automatic electron potentiometers are widely used in research and production work.

Thermometer calibration and their accuracy

Resistance thermometers and thermocouples are calibrated in water or oil thermostats or at high temperatures in tubular electric furnaces. Figure 33 shows a thermostat for the testing of thermometers in the temperature interval from 5 to $300^\circ C$.
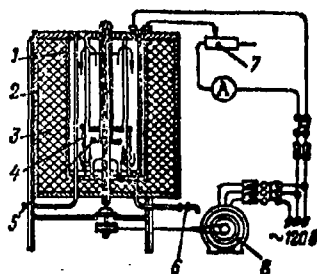

Fig. 33. Thermostat for the calibration of thermometers in the interval from 5 to 300°C. 1) Working vessel; 2) metal casing; 3) heat insulation; 4) heater; 5) agitator; 6) drain; 7) rheostat; 8) electric motor.

For purposes of qualitative calibration of thermometers the thermostat must satisfy a number of requirements:

1) the temperature field of the thermostat must be uniform, with a variation not to exceed $0.5^\circ C$;

2) in the time between two readings, the temperature of the liquid should not change by more than $0.1^\circ C$;

3) the level of the liquid in the thermostat during the process of the calibration must remain constant.

The specimen-standard mercury thermometers of the first or second class, with divisions of $0.1^\circ C$ in the interval from -70 to $+102^\circ C$, and
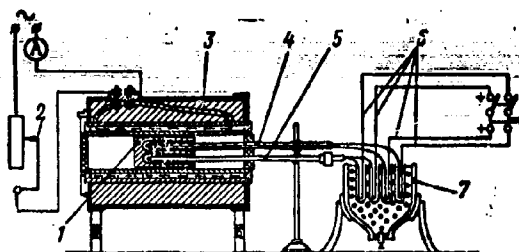
Fig. 34. Tubular electric furnace for calibration of thermocouples. 1) Metallic block; 2) rheostat; 3) electric furnace; 4) thermocouple being tested; 5) specimen-standard thermocouple; 6) connecting (copper) wires; 7) thermostat for cold junctions.

divisions of $0.2°C$ in the interval from +98 to $302°C$, serve as the control instruments during the calibration process.

A correction factor for the protruding column must be introduced into the readings of the mercury thermometer during the calibration. Verification for the negative-temperature range is conducted in ethyl alcohol cooled by carbon dioxide or freon.

The manner in which the thermocouples are placed inside the tubular electric furnace for purposes of calibration is shown in Fig. 34. The specimen-standard platinum/platinorhodium thermocouple, verified by the Committee of Standards, Measures, and Measurement Instruments, is used as the control instrument for the calibration.

The temperatures of the hot junctions of the control thermocouples and the one being calibrated must be identical, and for this purpose they are immersed into a nickel block as close as possible to one another and to an identical depth. It has been demonstrated experimentally that a difference of 5-7 mm in the immersion results in a difference of $7-10°C$ between the temperatures of the junctions. The thermoelectromotive forces of the thermocouples are measured by means of a laboratory potentiometer.

Information on the highest temperature-measurement precision is given in Table 3. The accuracy of the thermometers used for tests may vary. For example, the TUE-48 resistance thermometer which is used to measure the temperature of water, oil, or the outside air has a scale ranging from -70 to $+150^{\circ}$C and is graduated in 10°C divisions. The measurement error at normal temperature does not exceed $\pm1.5\%$.

The accuracy of the thermometers should not be confused with the accuracy of the temperature measurements, since in measurement practice it is rarely possible to equate the temperature of the sensing element with the temperature of the measured medium. The accuracy of the thermometer is determined by the accuracy with which the sensing element of the thermometer is able to measure the temperature.

3. FLOW AND RATE MEASUREMENTS

Over the past 50 years, in connection with the development of aviation and power engineering, the methods of measuring streams of gases have undergone significant development. Much work has been done in the USSR on pressure receivers and devices to measure temperatures in streams; this work has been carried out at the TsAGI (the Central Aerohydrodynamic Institute) and the TsKTI (the Central Boiler-Turbine Institute).

Measurement of flow temperature

It is comparatively simple to measure the temperature of a liquid moving at low speed. Figure 35 shows an example of an installation in which the sensing element of a resistance thermometer is used to measure the temperature of oil. To raise the accuracy of the measurement the channel walls must necessarily be insulated against heat and the sensing element must be positioned into the approaching stream.

The exact measurement of the temperature of a fast-moving hot gas is classified as a complex experimental problem. When the speed of the

- 73 -
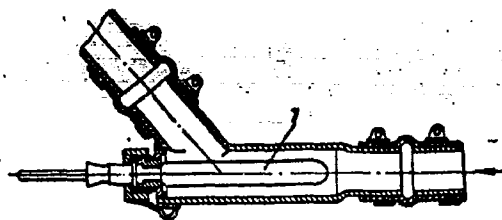
Fig. 35. Resistance-thermometer receiver in oil manifold. 1) Thermometer receiver [the sensing element].

flow is lower than 50 m/sec the temperatures of the moving gas and the gas at rest may be regarded as identical. In the case of faster speeds, however, the gas is decelerated at the sensing element and the gas temperature rises. The temperature of an adiabatically decelerated stream (i.e., in the absence of heat transfer between the measurement zone and the surrounding space) is calculated in accordance with the following formula:

$$T_t^* = T + \frac{Ac^2}{2gc_p},\qquad(72)$$

where T^*_t is the temperature of the adiabatically decelerated stream; T is the temperature of the moving gas; A is the thermal equivalent of mechanical work

$$(A = 1/427 \text{ kcal/kg-m});$$

g is the acceleration of the force of gravity; c_p is the specific heat of the gas at constant pressure; c is the velocity of the gas.

In actual fact there is always transfer of heat to the surrounding space. To take this transfer of heat to the surrounding medium into consideration and also to consider the incompleteness of deceleration, the temperature recovery factor r is introduced; at this point Formula (72) takes the form

$$T^* = T + r\frac{Ac^2}{2gc_p}.\qquad(73)$$

The temperature recovery factor r is determined from the following

- 74 -

Fig. 36. Diagram of screened thermocouple. 1) Channel wall; 2) screen; 3) thermoreceiver [heat sensing element].

expression:

$$r = \frac{T^* - T}{T_1^* - T}. \qquad (74)$$

The criterion M can be introduced into Formula (73):

$$T^* = T\left(1 + r\frac{k-1}{2} M^2\right). \qquad (75)$$

There are no theoretical methods of determining the magnitude of r and the recovery factor is therefore determined experimentally. Below stream temperatures of 300°C the quantity r is determined primarily by the stream deceleration ratio in the vicinity of the sensing element.

The thermocouple inserted in the stream radiates heat to the colder channel walls surrounding it. As a result of this radiation the temperature of the thermocouple is lower than the temperature of the gases which are flowing past it.

Let us examine the problem of heat transfer between the thermocouple and the surrounding medium (Fig. 36). Let us assume that screen 2 is temporarily lacking. Let T_1 be the temperature of the tube walls; T_3 the temperature of the thermocouple; T^*_t the temperature of the adiabatically decelerated gas.

The quantity of heat received by the thermocouple from the gases is determined by the following expression:

$$Q_\kappa = \alpha F_3(T_1^* - T_3), \qquad (76)$$

where α is the heat-transfer coefficient for the transfer of heat from the gas to the thermocouple; F_3 is the surface area of the thermocouple receiving the heat.

In the steady-state regime the quantity of heat received by the thermocouple is equal to the sum of the radiative heat scattered by the thermocouple to the channel walls and the heat removed through the

- 75 -

thermocouple and its casing.

The quantity of radiative heat released by the thermocouple is determined from the following formula:

$$Q_a = \varepsilon C_0 F_a \left[\left(\frac{T_3}{100}\right)^4 - \left(\frac{T_1}{100}\right)^4 \right].$$ \hfill (77)

where ε is the reference emissivity; C_0 is the coefficient of radiation.

The magnitude of the reference emissivity is determined by the following expression:

$$\varepsilon = \frac{1}{\frac{1}{\varepsilon_3} + \frac{F_3}{F_1}\left(\frac{1}{\varepsilon_1} - 1\right)}.$$ \hfill (78)

where ε_3 is the emissivity of the thermocouple; ε_1 is the relative coefficient of channel-surface radiation; F_1 is the surface of the channel wall participating in the transfer of heat with the thermocouple.

The ratio F_3/F_1 is close to zero and therefore

$$Q_a = C_0 \varepsilon_3 F_a \left[\left(\frac{T_3}{100}\right)^4 - \left(\frac{T_1}{100}\right)^4 \right].$$ \hfill (79)

In Formulas (77) and (79) $C_0 = 4.9$ kcal·m^2·hr·$^\circ$K^4, while the quantity ε_3 is a function of the material, the condition of its surface, and the temperature. For example, for a platinum wire $\varepsilon_3 = 0.073-0.182$ at a temperature of 225-1375°C; for iron $\varepsilon_3 = 0.08-0.13$ in the temperature range from 1000-1400°C.

Accepting the equality $Q_k = Q_1$ and neglecting the heat removed along the thermocouple and its casing, we will obtain

$$T_1^* - T_3 = \frac{C_0 \varepsilon_3}{\alpha} \left[\left(\frac{T_3}{100}\right)^4 - \left(\frac{T_1}{100}\right)^4 \right].$$ \hfill (80)

The considered formulas lead to the conclusion that the quantity T_3 is the closer to T^*_t, the smaller ε_3; the greater α, the closer T_1 to T_3. It is virtually impossible to affect the quantity ε_3.

It is possible to increase α by raising the speed of flow past the heat sensing element. This can be accomplished by the suction re-

moval of the gases surrounding the thermocouple. This method is somewhat complicated and another method is generally employed — the method of screening which makes it possible to bring the temperatures of the thermocouple T_3 and the gases T^*_t closer together.

If screen 2 is placed between channel wall 1 and thermocouple 3 (Fig. 36), the screen temperature T_3 will be higher than the temperature of the channel wall 1 being cooled, and this reduces the heat losses of the thermocouple. The thermocouple screens are generally designed so that they simultaneously act as deceleration chambers, i.e., chambers in which the gas flushes the thermocouples at reduced speed.

Let us consider the following example in order to evaluate the influence of screening [baffling] on the magnitude of the temperature-measurement error. Let the thermocouple indicate a temperature $T_3 = 1073^\circ K$ and let the temperature of the wall be equal to $T_1 = 773^\circ K$; $\alpha = 200$ kcal·hr·m^2·$^\circ K$ and $C_0 \varepsilon_3 = 4.22$. Then $T^*_t - T_3 = 204^\circ C$, i.e., the measurement error is very great.

The installation of screen 2 will reduce the difference $T^*_t - T_3$ to $37^\circ C$, i.e., the measurement error will be reduced by a factor of 5.5. A further reduction in the error can be achieved by introducing heat insulation for the channel walls and for the second screen. In measuring the temperatures of hot flows (exhibiting $T^*_t > 600^\circ K$) we find that the greatest source of error is the heat transfer.

Let us examine the design and test results for several thermoreceivers [heat sensing elements].

Deceleration chambers in which a thermocouple is positioned in the direction of the flow (horizontal deceleration chambers) or perpendicular to the approaching stream (vertical deceleration chambers) are used to decelerate the flow around the thermocouple. Sets consisting of several thermocouples positioned at specific points in a single

- 77 -

frame are used to measure temperature fields.

Figure 37 shows a heat sensing element with a vertical decelera-
tion chamber and the change in the temperature recovery factor r as a
function of the stream velocity (λ) and the relationship between the
areas of the inlet to and the outlet from the chamber ($K = F_{vykh}/F_{vkh}$)
is shown. The comparatively slight change in r with respect to the
velocity of the flow is characteristic of the given heat-sensing ele-
ment.

The thermoreceiver [heat-sensing element] to measure the tempera-
ture of a stream at speeds below $M = 1.2$ is shown in Fig. 38. The
thermoelectrodes are insulated by means of porcelain tubes. The rela-
tionship between the K areas for this heat-sensing element comes to
0.2.

The heat-sensing elements of precise (control) thermocouples ex-
hibit a somewhat more complex construction. As an example, in Fig. 39
we present the design of such a control thermoreceiver. One feature of
this thermoreceiver is the presence of four screens, of which the in-
side screen is made of ceramic material. The component parts of the
sensing element, flushed by the hot flow, are made of a heat-resistant
alloy.

Figure 40 shows the design of the TGZ-47 sensing element for the
measurement of the temperatures of decelerated gases.

The thermocouple is made of a nickel-cobalt alloy (NK) and special
alumel (SA). The outstanding characteristic of a thermocouple made of
NK and SA alloys consists in the fact that the thermoelectromotive
force arises when the temperature difference $t - t_0 > 300^o C$, as a re-
sult of which there is virtually no need for the introduction of a
correction factor for the cold junction temperature when working with
this thermocouple.

$$\tau = \frac{T^*_{\text{H}} - T}{T^*_{\text{H}} - T}$$
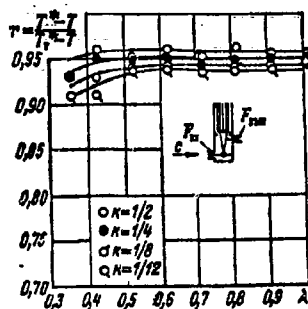
Fig. 37. Characteristic of thermoreceiver [heat-sensing element] with vertical deceleration chamber.
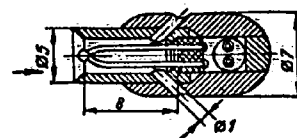
Fig. 38. Thermoreceiver [heat-sensing element] for measurement of flow temperatures.
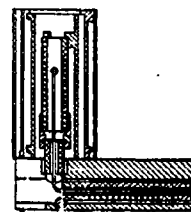
Fig. 39. Design of control thermoreceiver [heat-sensing element].
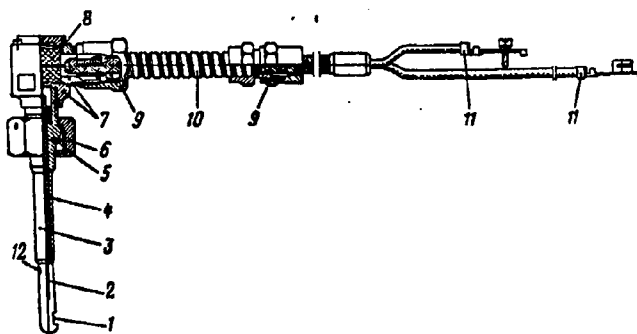
Fig. 40. Construction of the TGZ-47 heat-sensing element. 1) Sensing orifice; 2) thermocouple; 3) tube; 4) ceramic tube; 5) adjustment pin; 6) nut; 7) case; 8) ceramic blocks; 9) nut; 10) flexible hose; 11) contacts; 12) outlet.

Thermocouple 2 is insulated from tube 3 made of heat-resistant steel by ceramic tube 4. The thermocouple casing is positioned to face the gas stream through the inlet opening 1, 3 mm in diameter; the gas (at low speed) passes by the junction of thermocouple 2 and escapes

- 79 -
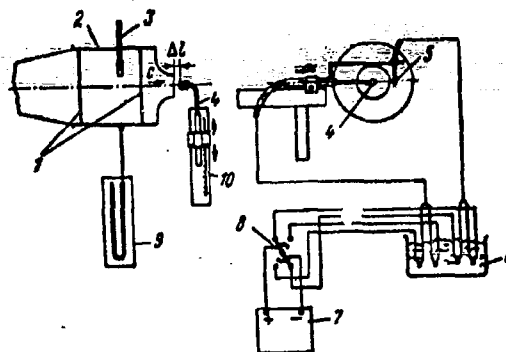
Fig. 41. Diagram of installation for
calibration of heat-sensing elements.
1) Grid; 2) antichamber; 3) thermo-
couple for maintenance of regime; 4)
control thermocouple; 5) thermocouple
being tested; 6) thermostat; 7) po-
tentiometer; 8) switch; 9) manometer;
10) coordinator.

through opening 12 that is 0.8 mm in diameter. Flexible hose 10 pro-
tects the wires from breaking. The connecting wires are connected to
contacts 11.

Regardless of the design, all of the heat-sensing elements must
be calibrated in special installations. One of the possible methods of
setting up the installation for purposes of calibrating heat-sensing
elements in a high-temperature stream is shown in Fig. 41. The control
thermocouple and then the thermocouple being calibrated are alternately
(by means of the coordinator) at the same point in the flow at the
nozzle exhaust. The regime must be kept constant for a period of 3-5
minutes to eliminate the effect of visual persistence.

Measurement of stream pressure and stream velocity

In testing VRD components one generally is called upon to measure
the pressure of moving liquids; in this event, the opening made into
the wall of the tube through which the liquid is flowing can serve as
a static-pressure sensing element. Total pressure is measured by means

- 80 -

of inserting a tube in such a manner as to have its open end face the approaching stream.

Let us examine the manner in which one can determine the velocity of a subsonic stream of gas by means of a combined tube. In the combined tube (Fig. 42) the total-pressure sensing element is the central orifice 1, while orifice 2 serves the function of the static-pressure sensing element. Deceleration in a subsonic stream follows the reversible adiabatic-curve law and the measured pressure p* is the pressure of the isentropic deceleration. The inlet orifices 2 are spaced apart to ensure the equality of the pressure applied to them and the static pressure $\underline{p}$ of the approaching stream. If $\underline{p}$ and p* are known, the λ of the stream is calculated in accordance with the well-known formula

$$\lambda = \sqrt{\frac{k+1}{k-1}\left[1 - \left(\frac{p}{p^*}\right)^{\frac{k-1}{k}}\right]},\qquad(81)$$

where $\underline{k}$ is the adiabatic exponent; otherwise, this quantity can be determined from gasdynamic tables.
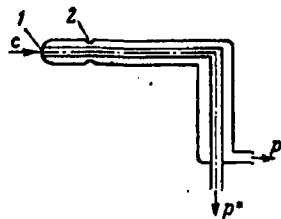
Fig. 42. Diagram of combined tube. 1) Total pressure sensing element; 2) static-pressure sensing element.

If the stagnation temperature is known, the critical velocity can be determined from the following expression:

$$a_{\text{кр}} = \sqrt{\frac{2}{k+1}gkRT^*},\qquad(82)$$

while the velocity of the stream is found from the following formula:

$$c = \lambda a.\qquad(83)$$

The speed of a supersonic flow can also be determined by a combined tube. But in this case orifices 2 of the tube are positioned so that the pressure $\underline{p}$ measured here is equal to the static pressure of the stream all the way to

- 81 -
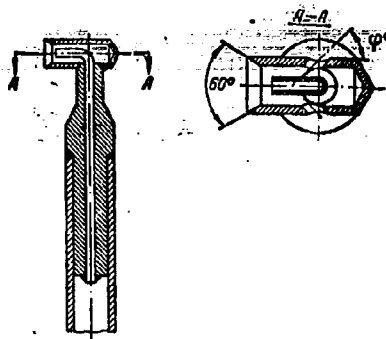
Fig. 43. Total-pressure sens-
ing element with channel.
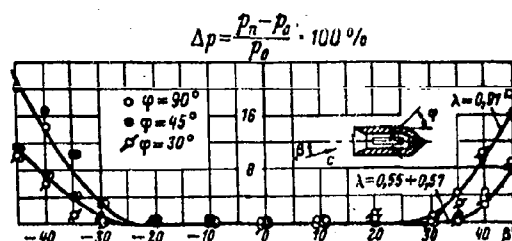
Fig. 44. Characteristics of total-
pressure sensing element with chan-
nel.

the normal shock which produces the deceleration.

Then the λ of the stream is calculated from the graph or from a
table of gasdynamic functions:

$$\frac{p}{p^*}=\left(\frac{1}{\lambda^2}-\frac{k-1}{k+1}\right)\left(1-\frac{k-1}{k+1}\frac{1}{\lambda^2}\right)^{\frac{1}{k-1}},\qquad(84)$$

where p is the static pressure in the stream prior to the compression
shock; p^* is the total pressure behind the compression shock.

It is most convenient to use those sensing elements exhibiting
but slight sensitivity to bending to measure total pressure in a
stream. Figures 43 and 44 show the designs and characteristics of a
sensing element that virtually does not distort the total pressure
when the velocity vector is deflected from the axis of the sensing ele-

- 82 -

ment through an angle of up to 25°.

An error in the measurement of total pressure is evaluated by means of the following formula:

$$\Delta p = \frac{p_\text{n} - p_0}{p_0} \cdot 100, \qquad (85)$$

where p_0 is the pressure measured where no bending occurred; p_p is the pressure indicated by the instrument.

A stream of air or gas passing through an engine exhibits a varying total pressure at various points. Therefore, in order to clarify the pattern of pressure losses and for purposes of determining velocities in a stream, a substantial quantity of total-pressure sensing elements are installed.

Figure 45 shows an example of an installation of total-pressure sensing elements on the edge of a guide-vane assembly blade. Cooled multipoint total-pressure sensing elements (rakes) are used for the measurement of the total pressure of a hot gas (for example, at the nozzle exhaust of a TRDF [turbojet-engine afterburner]).

The static pressure of a stream of gas is measured both at the boundaries of the stream and in its depths. The measurement of static pressures at the boundary of a stream is carried out by means of openings drilled into the walls containing the flow. As has been demonstrated by experiment, a slight (less than 10°) slant of the orifice axis to the wall exerts no influence on the accuracy of the readings. The drilled holes generally have diameters ranging between 0.3-1.2 mm. The edges of the holes must be finished and free of burrs.

Static pressures in a stream section are measured either by means of the aforementioned combined tubes or by means of special static-pressure sensing elements.

Figure 46 shows a needle sensing element for the measurement of

A *Приемник*

B *Разрез по приемнику*
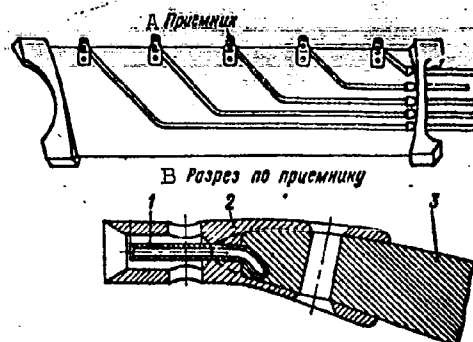
Fig. 45. Installation of total-pressure sensing elements on the edge of a guide-vane assembly blade. 1) Total-pressure tube; 2) sensing element case; 3) blade. A) Sensing element; B) sensing-element cross section.
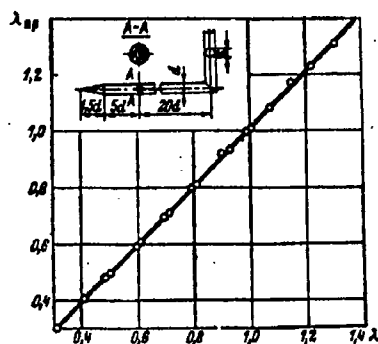
Fig. 46. Static-pressure needle sensing element.
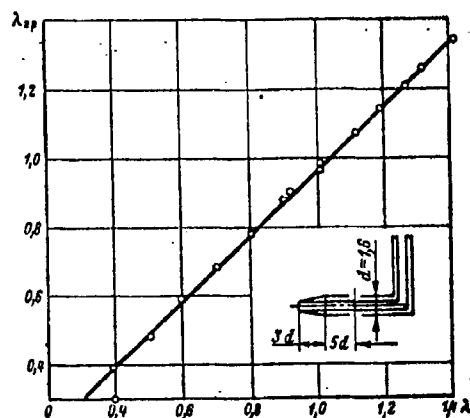
Fig. 47. Characteristics of combined sensing element.

static pressure and its characteristic with respect to λ is presented, i.c., λ_{pr} (instrument) as a function of λ (flow) at $d = 5$ mm and $\delta = 5$ mm.

A diagram of the combined sensing element for the measurement of total and static pressures, as well as its characteristic, is presented in Fig. 47. As we can see from the figure it has been possible to ob-

tain a linear characteristic throughout the entire range of changes in λ for this sensing element.

In tests of nozzles, turbines, and compressors, where it is preferable not to overload the section, the temperature and pressure of the flow can be measured by means of a single adjustable sensing-element coordinator.

A coordinator is a mechanism which makes it possible to install the sensing element in the required position and to record this position in rectangular or polar coordinates. Coordinators may be equipped either with manual or electric drive.

Measurement of stream direction

The direction of flow can be determined by means of a silk thread or by the immersion of a "wind vane." However, such determination of direction is inexact and occasionally impossible because of the intense vibration of the direction indicator.

In testing practice a pneumatometric method of determining the direction of a stream is used. Figure 48 shows a diagram of a pneumatometric sensing element which makes it possible (and more exactly with visual methods) to determine the direction of a stream in a plane, and the calibration curve for this instrument is also given.

The M(ach) number of the stream is plotted along the axis of abscissas, and along the axis of ordinates we have the derivative

$$\frac{d}{d\alpha}\left(2\,\frac{p_1-p_2}{\rho c^2}\right),$$

where p_1 and p_2 represent the pressures in tubes 1 and 2; ρ is the density of the gas; $\underline{c}$ is the velocity; and α is the angle of taper.

This graph can be used in the following manner. Let $\rho = 0.114$ kg × × sec^2/m^4, c = 170 m/sec, and M = 0.5; from the graph we will find

$$\frac{d}{d\alpha}\left(2\,\frac{p_1-p_2}{\rho c^2}\right)=0,0374$$

- 85 -
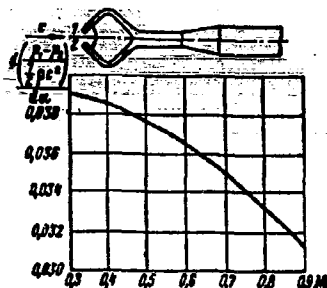
Fig. 48. Pneumatic
sensing element for the
measurement of stream
direction and the char-
acteristics of said
stream. 1 and 2) Inlet
tubes of sensing ele-
ment.
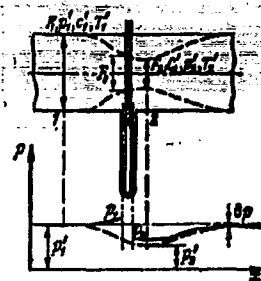
Fig. 49. Schematic
diagram of throttling
instrument (dia-
phragm) and the dis-
tribution of pres-
sures along the
length of the chan-
nel.

or

$$da = \frac{1}{0,0374} \, d \left(2 \frac{p_1 - p_2}{\rho c^2} \right).$$

Substituting the corresponding values for ρ and c, we will get

$$da = \frac{1}{61,5} \, d \, (p_1 - p_2).$$

If the difference

$$d(p_1 - p_2) = 60 \text{ kg/m}^2,$$

then

$$\Delta a \approx 1°.$$

The cited example shows that it is possible to determine the di-
rection of a stream with sufficient accuracy by means of a pneumato-
metric sensing element.

Measurement of liquid and gas flow rates by means of throttling in-
struments

To measure the flow rate of steady-state streams of liquids and
gases we employ throttling instruments, i.e., diaphragms and nozzles.
Let us examine the operating principle and the nature of the flow of a
liquid or gas through a throttling device on the basis of the example

- 86 -

of the diaphragm shown in Fig. 49.

Let us examine the flow of the gas in section 1-2. As we can see, in section 1 the flowing gas completely fills the tube. Two regions can be distinguished before and behind the diaphragm, i.e., a stream region and an annular-vortex region; the vortex region behind the diaphragm is significantly larger than in front of the diaphragm. As a result of the constriction in front of the diaphragm, the gas is accelerated both in the axial and radial directions, and this results in the appearance of corresponding pressure differences.

The change in pressure at the tube wall is shown by the solid line, while the pressure along the stream axis is given by a dashed line. The presence of radial pressure differences causes the narrowest stream section F_2 to shift into the region behind the diaphragm. The phenomenon is complicated by the presence of frictional forces at the boundaries of the stream.

Let us examine the simplified theory of a throttling device for an incompressible stream. Let friction be absent in section 1-2; in this case the D. Bernoulli equation is valid:

$$\frac{p_1'}{\gamma} + \frac{c_1'^2}{2g} = \frac{p_2'}{\gamma} + \frac{c_2'^2}{2g},$$

(86)

where c'_2 is the ideal velocity in the absence of friction (the remaining denotations are given in Fig. 49).

It follows from the equation that

$$p_1' - p_2' = \frac{\gamma}{2g}(c_2'^2 - c_1'^2).$$

(87)

The magnitude of the stream section F_2 can be expressed in terms of F_0:

$$F_2 = \mu F_0,$$

(88)

where μ is the convergence factor which is determined experimentally.

Taking into consideration the continuity equation

$$F_1 c_1' = F_2 c_2'$$ (89)

from Formulas (88) and (89) we will obtain

$$c_1' = c_2' \mu \frac{F_0}{F_1} .$$ (90)

Substituting the value of c'_1 from (90) into (87), we will obtain the value for the ideal velocity:

$$c_2' = \frac{1}{\sqrt{1 - \mu^2 \left(\frac{F_0}{F_1}\right)^2}} \sqrt{2g \frac{p_1' - p_2'}{\gamma}} .$$ (91)

In actual flow there are losses due to friction and the nonuniformity of velocity in section 2. Moreover, even in an ideal flow the averaged pressures p'_1 and p'_2 are not measured at all, but rather the pressures p_1 and p_2, i.e., in front of and behind the diaphragm. To take this point into consideration let us introduce the correction factor ξ; the value of the true velocity will then be

$$c_2 = \frac{\xi}{\sqrt{1 - \mu^2 \left(\frac{F_0}{F_1}\right)^2}} \sqrt{2g \frac{p_1 - p_2}{\gamma}} .$$ (92)

The weight flow rate of the incompressible gas can be calculated from the following formula:

$$G = F_2 \gamma c_2$$ (93)

After substitution of the values of F_2 and c_2 we will obtain

$$G = F_0 \frac{\mu \xi}{\sqrt{1 - \mu^2 \left(\frac{F_0}{F_1}\right)^2}} \sqrt{2g\gamma(p_1 - p_2)} .$$ (94)

It is rather difficult to determine the quantities μ and ξ separately and for this reason the following flow-rate factor is introduced in practical work:

$$\alpha = \frac{\mu \xi}{\sqrt{1 - \mu^2 \left(\frac{F_0}{F_1}\right)^2}} .$$ (95)

The flow rate can then be calculated from the following formula:

$$G = \alpha F_0 \sqrt{2g\gamma(p_1 - p_2)}. \qquad (96)$$

The quantity γ for gases is generally determined from the equation of state

$$\gamma = p_1/RT^*_1, \qquad (97)$$

where p_1 is the static pressure in front of the diaphragm; T^*_1 is the stagnation temperature of the stream in front of the diaphragm.

The temperature is measured at a distance equal to 10-20 tube diameters in order to eliminate the effect of the heat-sensing element on the flow in the throttling instrument and on the readings of the sensor. Thus the specific weight γ of the gas in the given formula is a conditional quantity.

In determining gas flow rates, we introduce a correction factor ε for the expansion of the medium being measured to account for compressibility and the formula for the calculation of the gas flow rate takes the following form:

$$G = \alpha\varepsilon F_0 \sqrt{2g\gamma(p_1 - p_2)}. \qquad (98)$$

For gases and vapors $\varepsilon < 1$; for liquids $\varepsilon = 1$.

The construction and dimensions of throttling instruments have been standardized. The method for the design of throttling devices is presented in the "Regulations 27-54 on the Application and Verification of Flowmeters with Normal Diaphragms, Nozzles, and Venturi Tubes."

Fig. 50. Standard diaphragm (a) and nozzle (b).

Figure 50 shows a standard diaphragm and nozzle and the design of the flange devices for the removal of pressure. The disk flange devices are shown in the upper parts of the sections, while the chamber flange devices are shown in the

- 89 -

lower part of the section.

Chamber devices are more complex and more expensive, but pressure measurements in annular channels yield more exact results, thus making it possible to reduce the length of the over-all section of the measuring device. Diaphragms are simpler than nozzles and have been studied more thoroughly, but in comparison with the nozzles they exhibit greater hydraulic resistance.

Throttling devices are used without calibration if $D \geq 50$ mm and d/D lies within a range from 0.2-0.85 for the diaphragms and 0.2-0.8 for the nozzles.

Materials not subject to corrosion are used for the fabrication of diaphragms and nozzles, i.e., stainless steel, brass, bronze, or ordinary steel with a protective coating.

The conditions under which diaphragms and nozzles are employed are extremely varied and therefore in calculating the flow rate of gases according to the readings given by throttling instruments it is necessary to introduce a number of correction factors.

The flow-rate coefficient may be represented in the form of the following product:

$$a = a_0 K_\mu K_{sh} K_k K_t,\qquad(99)$$

where a_0 is the initial flow-rate coefficient; K_μ is the correction factor for viscosity; K_{sh} is the correction factor for roughness; K_k is the correction factor for the bluntness of the edge; K_t is the correction factor for the thermal expansion of the diaphragm (nozzle).

The magnitudes of the correction factors depend on the parameters of the process and the design of the throttling instrument:

$$K_\mu = f\left(\frac{d}{D},\ \text{Re} = \frac{cD}{\nu}\right),$$

where ν is the coefficient of kinematic viscosity for the gas, in m^2/sec;

$$K_{\text{ш}}=\varphi\left(D,\frac{d}{D}\right);$$
$$K_{\mu}=\psi\left(D,\frac{d}{D}\right);$$
$$K_{t}=\eta(t).$$

There are curves for diaphragms and nozzles by means of which it is possible to find the values of the correction factors. Thus, for example, the quantity K_{μ} = 1.015 for a diaphragm when the tube diameter D = 100 mm and d/D = 0.5 (for Re = 10,000); K_{sh} = 1.008 and K_{k} = = 1.008.

Under the same conditions, for nozzles K_{μ} = 0.965 and K_{sh} = 1.000; the value of K_{k} is always equal to unity.

The quantity K_{t} is a function of the material used for the diaphragm (the nozzle) and of temperature. The values of the correction factor K_{t} for brass are presented in Table 9.

TABLE 9
Values of K_{t} for Diaphragms and Nozzles of Brass

$t°$ C	20	100	200	300	400	500
K_{t}	1.000	1,003	1,007	.1,011	1,015	1,019

In the selection of a diaphragm or a nozzle it is necessary to take into consideration the permissible magnitude of pressure losses, the possibility of fabrication, and the cost of the instrument and the operating conditions. It is also important to follow the instructions regarding the installation of throttling instruments. In the case of horizontal or inclined installation of the instruments it is necessary to provide openings, i.e., in measuring the flow rates of liquids, to release the air and vapor from the chambers, and to permit the settling of the condensate in the measurement of gas flow rates.

Rectilinear settling sections must be provided both in front of

Fig. 51.
Venturi
tube.

and behind the instrument. The lengths of the settling sections l_1 (in front of the instrument) and l_2 (behind the instrument) are functions of the presence of perturbing devices in the stream and a settling chamber, and they are also functions of the ratio d/D. For example, if there are valves in front of and behind the instrument, at $d/D = 0.5$ $l_1/D = 47$ and $l_2/D = 5$ are required for a diaphragm without a chamber while for a diaphragm with a chamber we require $l_1/D = 12$ and $l_2/D = 5$. This example demonstrates the extent of the role played by the chamber for the settling of pressure in the measurement zone.

A third type of throttling device — the Venturi tube (Fig. 51) — has found some application at testing stations for the measurement of great fuel flow rates. The primary advantage of the Venturi tube, in comparison with nozzles, and particularly in comparison with diaphragms, lies in its low resistance. In measuring fuel flow rates it is completely suitable in terms of dimensions and operationally reliable.

Volume flowmeters

"Samplers" and rotary flowmeters (the latter can be used for the measurement of gas flow rates as well) are used for the measurement of liquid volume flow rates.

Figure 52 shows a "sampler" with photocells to note the time at which the fuel level passes the control grooves. A "sampler" is part of the fuel system.

Flow tank 2 is connected to frame 15 of the floating valve by means of a sleeve with orifices 1. Disks 13 are seated on the central tube 3 and these disks separate the measuring chambers. Window 4 provides for visual observation of the passage of fuel through the measur-

ing channels. Bypass 5 with connection tube 6 for fuel passage links flow tank 2 with compensation tank 10.

In compensation tank 10 there is window 7 for observation of the liquid level in regulating the counterpressure. Overflow tube 9 provides for the passage of air from compensation tank 10 to flow tank 2. Air pressure in compensation tank 10 is controlled by a valve set into cover 8. Connection tube 6 and the frame of valve 20 are connected with the manifold supplying fuel to the "sampler," while the outlet connection tube 17 is connected with the manifold supplying fuel to the engine. Photocells 12 are mounted in the column and "observe" the passage of fuel at disks 13 of the measuring chamber.

During engine operation the float in frame 15 is in its top position and the lever rests against plate 16, as shown in the diagram. If lever 18 of cam 21 is vertical, the cam holds valve 22 open. The cam spring in this case is at its minimum length. The fuel passes through the valve into frame 15 of the floating valve and then into the engine.

The tube supplying fuel to the compensation tank through connection tube 6 and the flow tank 2 are filled with fuel, while the greatest part of the compensation tank 10 is filled with air. The level of fuel in the compensation tank can be controlled by changing the air pressure with the valve mounted in cover 8.

To measure the fuel flow rate the shaft of cam 21 is turned manually to the position shown in the diagram. In this case valve 22 closes and lever 18 of cam 21 moves in behind cam 19 of the float. Since the valve is closed, the fuel begins to flow from the flow tank 2 and air from compensation tank 10 begins to take its place. Fuel enters the newly vacated space in tank 10 through connection tube 6. Tube 9 prevents this fuel from overflowing into flow tank 2 so long as the fuel in tank 10 has not reached the upper rim of tube 9. When the fuel level

- 93 -

reaches the floating chamber the float descends and the float cam 19, turning, releases lever 18.
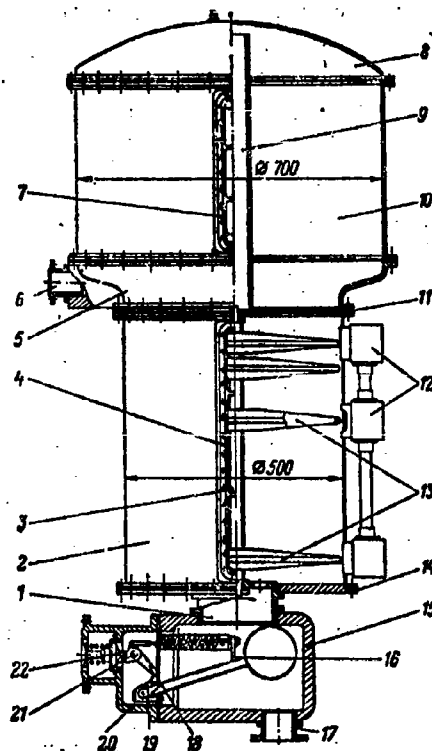
Fig. 52. "Sampler." 1) Sleeve; 2) flow tank; 3) central tube; 4) window; 5) bypass; 6) connection tube; 7) window of compensation tank; 8) cover; 9) overflow tube; 10) compensation tank; 11) upper flange; 12) photocells; 13) disks; 14) lower flange; 15) frame [case] of floating valve; 16) plate lock; 17) outlet connection tube; 18) lever; 19) float cam; 20) valve case; 21) opening cam; 22) inlet valve.

The spring turns cam 21 and automatically opens valve 22. In this case the fuel enters the engine and through sleeve 1 proceeds into flow tank 2, while air again flows into compensation tank 10.

The time required for the fuel to pass disks 13 of flow tank 2 is recorded by photocells 12. The space between disks 13 is known exactly
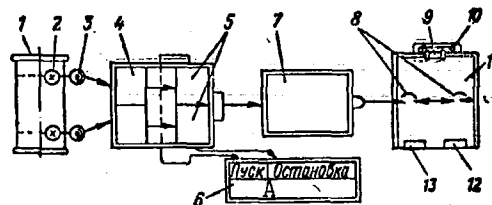
Fig. 53. Diagram of automatic fuel
flow rate measurement system. 1)
"Sampler"; 2) illumination light; 3)
photocell; 4) amplifier; 5) thyra-
tron relay; 6) chronograph; 7) high-
voltage generator; 8) spark flash;
9) objective; 10) film; 11) camera;
12) turn counter; 13) timer.
A) Start/stop.

(it is determined during the period of calibration). The fuel flow
rate is calculated from data on the measurement of the metering cham-
ber, the time of fuel consumption, and the specific weight of the fuel.

The fuel level in compensation tank 10 can be regulated so that
as the fuel reaches the upper rim of sleeve 1 it begins to flow through
tube 9 into flow tank 2 and engine feed is not disrupted even if the
system of valve 22 fails to function satisfactorily (for example, if
the spring of cam 21 should break).

The photocells are incorporated in the system for the automatic
measurement of fuel flow rate that is shown in Fig. 53. When the fuel
level passes the region "observed" by the photocell, it releases a sig-
nal through amplifier 4 and the thyratron relay 5 to the "start" of
chronograph 6 and the spark flash 8 of the camera. At the instant of
the spark flash the readings of timer 13 and the turn counter 12 for
the engine shaft are photographed.

Figure 54 shows the diagram of a rotating counter with oval gears
which, when engaged with one another, turn under the action of the liq-
uid pressure differences across the inlet to and outlet from the in-
strument.

- 95 -
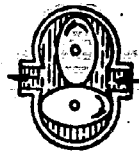
Fig. 54. Diagram
of rotary counter.
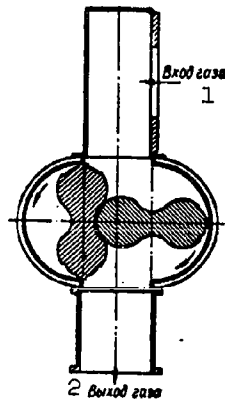
Fig. 55. Diagram
of rotating gas
counter. 1) Gas
inlet; 2) gas out-
let.

The volumetric flow rate of the fuel is determined from the counting mechanism or it is calculated in accordance with the following formula:

$$V = \eta \frac{n}{60} 4 V_1.$$
(100)

where V_1 is the volume encompassed by the gears; η is the fill factor by means of which we take into consideration the losses through the clearances; $\underline{n}$ is the shaft rpm.

Standard counters of this type are suitable in terms of dimensions and weight only for operations under ground conditions.

Figure 55 shows a diagram of a rotating gas counter. The blades ("figure-eights"), mounted in the counter case, are shaped so that they touch neither the case nor one another; gears situated beyond the limits of the working cavity transmit rotation from one blade to another. The blades are set into rotation by the pressure difference between the inlet and the outlet; this difference on a normally functioning counter does not exceed 30 mm water column.

Rotating counters are reliable in operation and rather exact, but they do not offer high capacity. Flowmeters of this type may also be used for the measurement of nonsteady-state flow rates.

Rotameters

The construction of a rotameter is shown in Fig. 56. A [metering] float 2 is positioned in the rising stream of fuel in a conic [rotameter] tube 1 which has a scale. As the liquid moves the float is car-

Fig. 56. Diagram of rotameter. 1) Conic tube; 2) float.

ried to a point at which its excess weight is equal to the buoyant force which is a function of the speed with which the liquid flows past the float. The excess weight is equal to the difference between the weight of the float in a vacuum and the weight of the liquid displaced by the float.

Let us write the equilibrium equation for the float in a liquid stream

$$G_\text{п} \quad V_\text{п}(\gamma_\text{п} - \gamma_\text{т}) = c_x \frac{\gamma_\text{т}}{g} f_\text{п} c_\text{т}^2, \qquad (101)$$

where G_p is the excess weight of the float; V_p is the volume of the float; γ_p is the specific weight of the float; γ_t is the specific weight of the fuel (measured with a hydrometer); c_x is the coefficient of frontal float resistance, a function of fuel viscosity, fuel flow rate, and float shape, as well as of the position of the float; f_p is the area of the maximum cross section of the float; c_t is the flow rate of the liquid in front of the float.

After a simple transformation we will obtain an expression for the determination of the volumetric flow rate of fuel:

$$Q = f_p \sqrt{\frac{V_\text{п} g}{f_\text{п} c_x} \cdot \frac{\gamma_\text{п} - \gamma_\text{т}}{\gamma_\text{т}}}, \qquad (102)$$

where f_p is the area of the tube cross section.

Rotameters are compact, they are simple, and they provide the instantaneous value of the volumetric fuel flow rate. They are suitable also for the measurement of gas flow rates. However, rotameter readings depend on the specific weight of the fluid, its viscosity, and on temperature. This reduces measurement accuracy significantly.

The gravimetric method of measuring fuel flow rate

The installation for the measurement of fuel flow rates by the

gravimetric method (Fig. 57) consists of scales 3, a flow tank 7, a compensation tank 5, flexible hoses 6 and 8, compensation tube 2, a three-way valve 9, and an air valve 4.

To fill the installation valve 9 is set to position a, valve 4 is closed, and valve 1 is open. The fuel from the manifold fills tank 7 and a portion of compensation tank 5. Valve 4 serves to control the air pressure in compensation tank 5 and the instant at which the fuel overflows into tank 7.

For purposes of measuring fuel flow rate, the three-way valve 9 is set to position b and the time and the weight of the fuel taken from tank 7 are measured. Depending on the flow rate, tank 5 is filled with fuel through compensation tube 2; when the level of fuel in tank 5 reaches the upper rim of the overflow tube, the fuel begins to flow over into tank 7 and measurement becomes impossible.
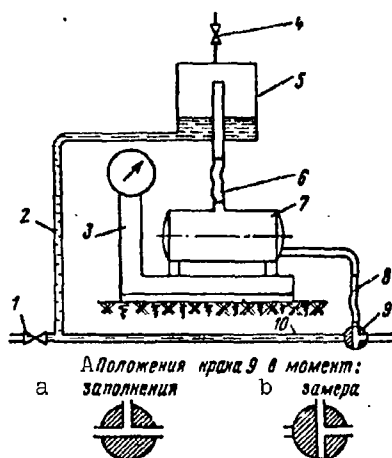

Fig. 57. Diagram of installation for gravimetric measurement of fuel flow rate.
1) Manifold valve; 2) compensation tube; 3) scales; 4) air valve; 5) compensation tank; 6, 8) flexible hoses; 7) flow tank; 9) three-way valve; 10) fuel manifold. A) Position of valve 9 at instant of: a) filling; b) measurement.

The scales must be of the indicator type and rather sensitive. The sensitivity of these scales in the system can be checked by observing their reaction to slight load in the case of the flow rates corresponding to the three basic engine operating regimes. The gravimetric measurement method is more complicated than the volumetric method, but it requires no measurement of the specific weight of the liquid (fuel, oil).

Accuracy of flow and flow-rate measurements

Data on the maximum accuracy achieved in the measurement of the temperatures of nonmoving media and the measurement accuracy achieved with industrial thermometers are presented in Tables 10 and 11.

TABLE 10

Metrological (Maximum) Accuracy in Temperature Measurement

1 Температура стоградусной шкалы °C	2 Погрешность измерения °C	3 Наименование прибора
—183	±0,005	4 Термометр сопротивления эталонный
0	±0,003	5 То же
100	±0,005	То же
444,6	±0,012	То же
500	±0,020	6 Термометр сопротивления образцовый
600	±0,100	7 Термопара платинородий-платиновая, эталонная
1300	±0,200	То же
2000	±4,0	8 Оптический пирометр эталонный
3000	±5,5	То же

1) Temperature of centigrade scale, in °C; 2) measurement error, in °C; 3) designation of instrument; 4) standard resistance thermometer; 5) the same; 6) specimen-standard resistance thermometer; 7) platinorhodium-platinum standard thermocouple; 8) standard optical pyrometer.

The errors in the temperature measurements of fast-moving gases result from other causes.

With proper selection of the shape and dimensions of the decelera-

TABLE 11

Accuracy of Measuring Temperatures of Media by Means of Industrial Thermometers

1 Температура стоградусной шкалы °C	2 Погрешность измерения %	3 Наименование приборов
—183÷600	±1,0÷1,5 от верхнего предела шкалы (4)	6Термометр сопротивления
600÷1300	±0,3	7Термопара платинородий-платиновая
600÷1300	±1,0 ⎫ 5 от измеряемой температуры	8Термопара хромель-алюмелевая
до 1400	1	9Оптический пирометр
до 2000	1 ⎭	То же 10

1) Temperature of centigrade scale, in °C; 2) measurement error, in %; 3) designation of instruments; 4) ... of upper limit of scale; 5) ... of measured temperature; 6) resistance thermometer; 7) platinorhodium-platinum thermocouple; 8) chromel-alumel thermocouple; 9) optical pyrometer; 10) the same.

tion chamber which simultaneously functions in the role of a single-ply screen, the thermocouple measurement errors in flow below 900°C can be assumed to be equal to ±1.0-1.5%. This error is obtained upon the insertion of a heat-sensing element into an uncooled tube and during the measurement of the thermal emf with a PP-type potentiometer.

The accuracy of stream-temperature measurements with series-produced electrical resistance thermometers is characterized by the following data.

The standardized TUE-48 electrical resistance thermometer for the measurement of oil, water, and air temperatures in the range from —70 to ±150°C yields an error of ±4.3%. The error of the TGZ-47 thermocouple in the working range from 400-900°C, according to data from the manufacturing calibration process, amounts to 8-20°C. When mounted in an engine, this [thermocouple] error increases as a result of intensified heat transfer.

In measuring the pressures of moving gases, it is necessary to add the errors of the pressure-sensing elements to the manometer errors. The errors of the total-pressure sensing elements in subsonic and supersonic flows are very small.

The measurement of static pressures, as a rule, is less exact. Static-pressure sensing elements yield an error generally not higher than 1.5%.

The accuracy of the determination of λ for a flow is governed by the accuracy of the pressure measurements. For needle sensing elements the mean square error of the calibrations, determined from the deviation of the experimental points from the linear characteristic, does not exceed 0.6% in the range $\lambda = 0.3$-1.4.

In the manufacture of throttling instruments in exact conformity with Regulations 27-54, flow-measurement accuracy can be achieved with an error of the order of $\pm 1\%$. The error of the throttling instruments rises sharply when measuring the flow rates of pulsating streams and may involve tens of percent.

The measurement accuracy of fuel flow rates in the case of "samplers" depends on the accuracy of calibration, specific-weight determination, and time measurement. Time is measured by means of a conventional timer exhibiting an error of about 0.3 sec, while the human [experimenter's] error in reading the time of fuel-level passage comes to about 0.2-0.3 sec.

In the case of measurements lasting 30 sec, the error in the estimation of the fuel flow rate is of the order of 1.5%. If the volume of the flasks used in this case is increased and calculated for 60 sec, and if a chronoscope with a balance-oscillation half-period of 0.01 to 0.02 sec is used as the timer, the error is of the order of $\pm 0.5\%$. The accuracy can be increased by employing automatic recording of the time

required for the fuel to flow out of the measuring chamber.

The error of volumetric counters with oval gears (SVSh 5-16/40) is equal to ±0.5% of the measured quantity. The error in the case of rotameters is equal approximately to ±2.5%.

The accuracy in the gravimetric method of measuring fuel flow rate is determined by the accuracy of the scales and the accuracy of time recording for the fuel flow. The scale-measurement accuracy is of the order of ±0.2%. If a chronoscope and a photocell are used for purposes of time recording, in measuring flow rate for a period of 30 sec (the measurement error in the case of time is of the order of 0.1 sec) we will obtain a total error of the order of ±0.5%.

To increase the measurement accuracy with the given equipment, we can recommend the method of multiple measurements. The results are evaluated by averaging the derived data.

4. GAS ANALYSIS

The gas analysis of the products of combustion is carried out only in the case of special investigations conducted on combustion chambers. Two types of gas analyzers have gained acceptance in practice, i.e., chemical and electrical analyzers. The electrical gas analyzers are less precise.

Among the simplest analyzers is the portable GKhPZ chemical gas analyzer which determines the percentage content of CO, CO_2, and O_2. The operation of the gas analyzer is based on the capacity of solutions to absorb gases and involves the measurement of the volume of gas that remains unabsorbed.

Figure 58 shows a diagram of a GKhPZ analyzer. The working parts of the GKhPZ are made of glass. The gas is taken into burette 8 having a volume of 100 ml; the volume of the gas after absorption is measured by means of this same burette. The lower part of the burette, used in
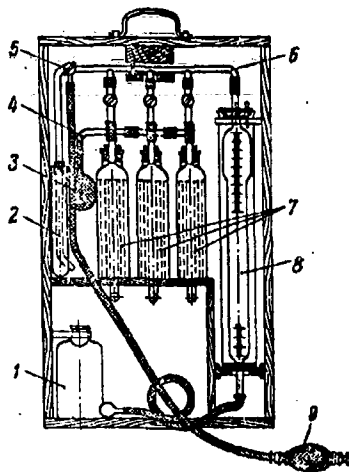
Fig. 58. Diagram of gas analyzer. 1) Leveling vessel; 2) filter; 3) rubber sack; 4) connection tube; 5) three-way valve; 6) distributor tube; 7) absorbers; 8) burette; 9) bulb.

the determination of the absorbed gases, permits the measurement of the gas volume more exactly than the upper part (since it has a smaller diameter). The burette is immersed in a water-filled vessel, thus reducing the temperature fluctuations during the course of the gas analysis.

The absorber vessels 7 (the U-shaped vessels) are filled with glass tubes and absorbent solutions; the tubes increase the absorption surface and thus speed up the process of the analysis.

Distributor tube 6 connects vessels 7 and burette 8 to gas filter 2 or bulb 9 (depending on the position of three-way valve 5). The glass-wool packed U-shaped tube which is gas filter 2 traps the solid particles that are in the gas that is being analyzed. Bulb 9 is used to suck the gas through filter 2 and to flush the distributor tube 6 with the test gas coming in from burette 8. Tube 4 connects the absorber vessels 7 with the rubber sack 3 sealing the system from the air.

Gas analysis can be divided into two operations, i.e., preparation and the actual analysis.

In the preparatory stage filter 2 is connected by means of the cooled copper tube to the gas separator; valve 5 connects the manifold and filter 2 with bulb 9 which provides for gas suction. Burette 8 and tube 6 are flushed with gas by means of leveling vessel 1 and bulb 9; the gas is taken into burette 8 by lowering vessel 1 with the trapping liquid. Then the gas-air mixture is removed by raising vessel 1 and

- 103 -

bulb 9.

After the system is flushed it is filled with a pure sample of the gas being analyzed. Valve 5 of the measuring system is insulated from filter 2 and bulb 9. The pressure in the system must be equal to the outside pressure (i.e., the level of the trapping liquid in burette 8 must be identical to the level in vessel 1).

The valve of the first absorber vessel 7 is opened and the leveling vessel 1 is raised in order to carry out the analysis; the gas is passed from the burette to the absorber vessel several times; when vessel 7 is filled with gas, the liquid is removed to another part (the U-shaped vessel), and the air is taken through tube 4 to sack 3.

Upon the completion of the absorption in the first absorber vessel, the valve of this vessel is closed off and the volume of the remaining gas is determined. The operation is then repeated with the other vessels. In measuring the volume of the unabsorbed gas, the levels in vessel 1 and burette 8 must be made to coincide.

Salt water (sometimes, mercury) is used as the trapping liquid in the leveling vessel. A solution of 100 g of caustic potash (KOH) in 200 g of distilled water is used for the absorption of CO_2; a solution of 80 g of KOH and 30 g of pyrogallol in 100 g of distilled water is used for the absorption of O_2; for the absorption of CO a solution of 250 g of ammonium chloride (NH_4Cl) is used together with 200 g of cuprous chloride in 750 g of distilled water. Only the nitrogen remains unabsorbed.

The accuracy of this method of determining the composition of a gas is approximately 0.1-0.2%.

5. MEASUREMENT OF THRUST AND MOMENT

The measurement of thrust is a necessary element in the testing of all air-reaction engines including turbojet engines; in the testing

of these engines it is, moreover, also necessary to measure the magnitude of torque.

The measurement of thrust or a moment can be reduced to the measurement of the forces for the determination of which the following are used: lever dynamometers, dynamometers, spring dynamometers with electrical sensing elements, etc.

Lever dynamometers

Figure 59 shows a diagram of a lever dynamometer with an optical system of transmitting readings and magnifying the scale.

The force of engine thrust (or the force due to the moment) is transmitted by the movable platform 1 on which the engine is mounted through connection 2, the intermediate connecting rod 3, the horizontal Γ-shaped lever 4 and the scale connecting rod 5 (force causes connecting rod 5 to expand). The force of thrust is picked up by the vertical Γ-shaped lever 16 and this is transmitted by means of the intermediate coupling rod 17 to the lever 18 of the dynamometer. Weight 6 for the preliminary loading of the system and oil damper 19 for the attenuation of system vibrations are attached to lever 18.

The force is then transmitted through connecting rod 7 to the lever with weight 14 that serves to determine the values of the divisions, and this lever also carries damper 15 which attenuates the vibrations and reduces changes in the load.

Then the force is transmitted to a pendulum with weight 9 which balances the force being measured; this transmission proceeds through the rod and steel strip resting against the profile. With a change in force scale 12 shifts and its readings are transmitted to the dynamometer screen 13 by means of bulbs 10 and the mirror system 11.

The dynamometer under consideration is extremely simple and reliable in operation. However, vibrations may cause the mechanical system

- 105 -
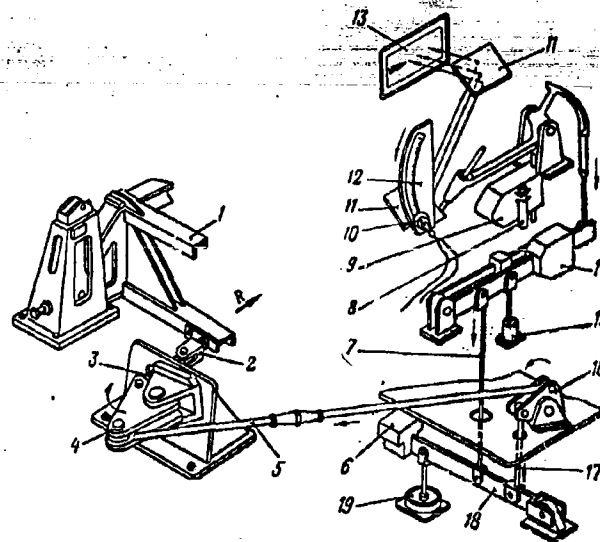
Fig. 59. Diagram of lever dynamometer with an
optical system for the transmission and magni-
fication of the scale. 1) Moving platform of
the stand; 2) transmission connection; 3) in-
termediate coupling rod; 4) horizontal Γ-
shaped lever; 5) coupling rod to scales; 6)
load for preliminary loading of system; 7)
vertical coupling rod; 8) exact-adjustment
screw; 9) balancing load; 10) optical system
(bulb); 11) mirror; 12) dynamometer scale; 13)
dynamometer screen; 14) scale division setting
weight; 15) damper; 16) vertical Γ-shaped
lever; 17) intermediate connecting rod; 18)
dynamometer sensing lever; 19) damper.

to experience resonance vibrations and this markedly reduces measure-
ment accuracy. The dynamometer system can be tuned to eliminate this
drawback.

Moreover, there are many hinges in the dynamometer system involv-
ing the use of antifriction bearings. During operation the bearings
must be protected against contamination by dirt or water, since the
accuracy of the dynamometer is reduced if these bearings become fouled.
The appearance of rough spots on the bearing races also affect measure-
ment accuracy. Therefore, in measuring systems of this type every ef-

- 106 -

fort is made to fabricate the hinges in the form of prisms or flexible bands.

Liquid dynamometers

In actual practice laboratories and testing stations make use of nonflowthrough and flowthrough liquid dynamometers.

The nonflowthrough dynamometers (i.e., without a constant flow of liquid), having a rotating cylinder or piston set into motion by a special electric motor, are complicated but exhibit higher accuracy
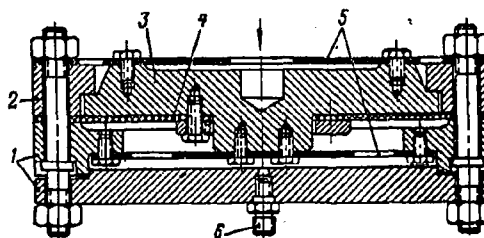
Fig. 60. Nonflowthrough dynamometer with distributor diaphragm. 1) Case; 2) lock ring; 3) piston; 4) diaphragm; 5) guide diaphragms; 6) connection tube.

than other nonflowthrough dynamometers. Dynamometers with distributor diaphragms are structurally simple but require the absolute airtight construction for exact measurements that is lacking in a system of air containers and the system must moreover be insensitive to fluctuations in temperature.

Figure 60 shows a nonflowthrough dynamometer with a distributor diaphragm. The liquid dynamometer consists of piston 3, case 1, and distributor diaphragm 4. The lock ring 2 restricts the piston stroke and the flexible diaphragms 5 direct its motion. Connection tube 6 is used to measure oil pressure.

A liquid dynamometer operates in the following manner. The force to be measured is applied normally to the piston and balanced by the
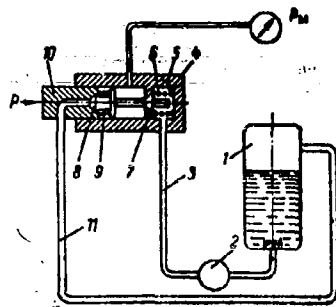
Fig. 61. Diagram of piston dynamometer with variable [adjustable] oil inlet and outlet area. 1) Oil tank; 2) oil pump; 3) inlet manifold; 4) receiver chamber; 5) dynamometer cylinder; 6) inlet-valve spring; 7) inlet valve; 8) outlet valve; 9) outlet-valve spring; 10) piston; 11) outlet manifold.

counteraction of diaphragms 5, diaphragms 4, and the pressure of the working fluid. Transformer oil, glycerine, a mixture of glycerine and alcohol, and other liquids are used as the working fluids, insofar as they are capable of maintaining their low viscosity when the temperature of the surrounding medium is low. The pressure of the working fluid is measured by a precise manometer that is calibrated for the force being measured. The effect of diaphragm flexibility is taken into consideration in the calibration. The piston stroke must be small — of the order of 0.05-0.10 mm. If there are air sacks in the system and the temperature exerts an effect on the chamber containing the liquid, measurement accuracy is reduced. These shortcomings are absent, to a significant degree, in the flowthrough dynamometer.

Figure 61 shows a diagram of a flowthrough dynamometer in which the inlet and outlet areas can be regulated. The oil passes from oil tank 1 through the filter into oil pump 2 in which there is a reduction valve that keeps the pressure in the inlet manifold 3 constant, knowing beforehand that this pressure is higher than might be required in the power-measurement device.

The oil is supplied to the receiver chamber 4 of the dynamometer cylinder 5 under high pressure (for example, at 50 kg/cm^2). There is a spring 6 and an inlet shutoff valve 7 in the receiver chamber 4. The outlet valve 8 together with spring 9 are seated on a common shaft with the inlet valve 7. There is an orifice in piston 10 for the ejec-

- 108 -

tion of oil through manifold 11 into the oil tank. Under the action of the force P being measured piston 10 shifts and valve 7 opens. The oil enters the piston cavity until force P is balanced by the oil pressure and the force acting in the valve system.
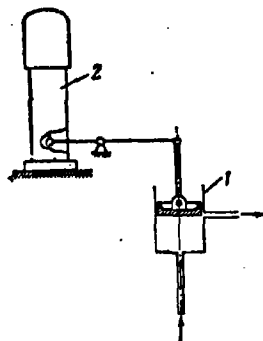
Fig. 62. Diagram of precise oil-pressure measurement in dynamometer. 1) Hydraulic sensing element; 2) accurate scales.

If force P is reduced, the piston will move to the left, valve 7 will close the inflow of oil, and valve 8 will open the outlet orifice causing the oil pressure in the piston cavity to drop. The oil pressure in the piston cavity is measured with high accuracy — of the order of $\pm 0.1\%$.

A hydraulic sensing element 1 (Fig. 62) with precision pendulum balances 2. The oil from the piston cavity is carried to the hydraulic sensing element of the dynamometer; the force acting on the piston of the hydraulic sensing element is offset by the precision pendulum balances. The entire measurement system is calibrated by means of precise weights.

Figure 63 shows a cross section of a diaphragm flowthrough dynamometer operating on the same principle as the flowthrough piston dynamometer, since the measurement of force in the flowthrough dynamometer is carried out at the instant of equilibrium, air bubbles and changes in temperature conditions exert virtually no influence on the accuracy of the readings. The pistons of the dynamometers execute extremely small strokes. The reduction in the piston stroke of the dynamometers raises the measurement accuracy.

Of considerable interest for the techniques of testing turboprop engines is the torquemeter (IKM — [izmeritel' krutyashchego momenta]). The IKM [torquemeter] is a component part of a TVD [turboprop engine]

- 109 -
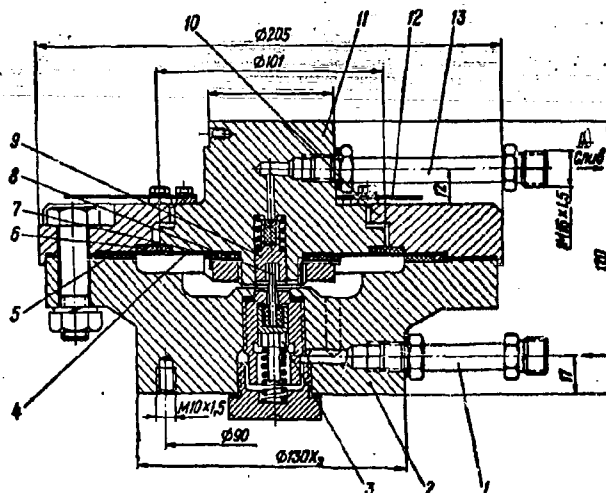
Fig. 63. Design of flowthrough dynamometer
with adjustable oil inlet and outlet areas. 1)
Inlet connection tube; 2) cylinder; 3) inlet
valve with spring; 4) steel diaphragm; 5, 7)
fiber spacers; 6) rubber spacer; 8) plunger;
9) outlet valve with spring; 10) limiter ring;
11) piston; 12) plates preventing the bending
of the piston; 13) outlet connection tube. A)
Drain.
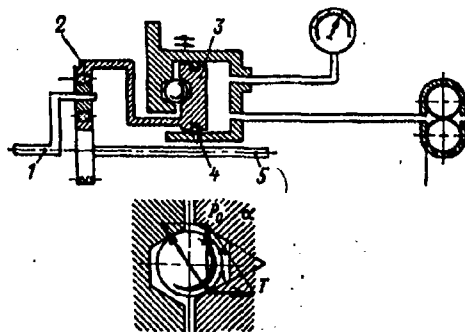
Fig. 64. Schematic diagram of hy-
draulic IKM with rollers. 1) En-
gine shaft; 2) gear wheel; 3) pis-
ton; 4) oil-drain orifice; 5) out-
let shaft.

and makes it possible to measure torque both on a test-station stand

and in flight.

The hydraulic IKM [torquemeters] are the most common. One of the possible versions of a hydraulic IKM is shown in Fig. 64. A reaction moment is applied to the fixed gear wheel 2 during the transmission of engine power through a planet gear to the outlet shaft 5; the wheel moment (force P_0) is transmitted to the housing of the reduction gear through rollers that transform the rotational motion of the wheel into the translational motion of pistons 3 (under the action of force T). The stroke of piston 3 is halted at the instant when the force acting on the piston is balanced by the oil pressure that is increasing as a result of the reduction in the area of the outlet orifice. Oil pressure gives an indication as to the magnitude of the torque.

Because of inadequate accuracy on the part of the TKM [torque-meter] it is not yet possible to eliminate the test-stand systems of measuring torque, although IKM [torquemeters] have gained considerable acceptance in turboprop-engine operation.

Spring dynamometers with electrical sensing elements

The acting force in such dynamometers is absorbed by the spring and deforms it. The deformation of the spring may be measured by induction, tensometer [strain gauge], or similar sensing elements. Figure 65 shows one of the possible circuits of an induction meter for deformations. In this circuit the voltage of the output diagonal of the bridge

$$\Delta U = kU\delta, \qquad (103)$$
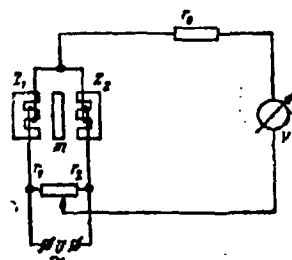
Fig. 65. Circuit of deformation induction meter. m) Armature; z_1, z_2) magnets; r_1, r_2) resistances; r_0) control resistance; U) clamp voltage.

where k is a coefficient that is a function of the design of the coils r_1 and r_2; U is the AC voltage applied to the bridge; δ is the shift of the armature m from its neutral position.

- 111 -

The shift δ of the armature disrupts the equilibrium of the bridge and the quantity ΔU is proportional to this shift. The armature may be connected to an elastic element which absorbs the force being measured; thus the magnitude of the force can be read off from a properly calibrated millivoltmeter scale.

Accuracy in the measurement of forces and moments

The methods and instruments described above for the determination of forces yield various errors.

By means of nonflowthrough dynamometers in which oil pressure is measured by means of a piston manometer, active forces can be measured with an accuracy of ±0.2%. In this case, an error of ±0.1% is attributable to the piston manometer, while ±0.1% results from the dynamometer.

Approximately the same accuracy is offered by the flowthrough dynamometers, but it is significantly easier to achieve this accuracy, since in this case no absolute airtight construction nor cleaning of air bubbles from the system are required, and moreover changes in the temperature of the surrounding medium are not as significant.

Spring dynamometers do not, as yet, provide the required accuracy.

6. MEASUREMENT OF REVOLUTIONS

Instruments for the determination of engine and machine rpm are known as tachometers and counters. In testing practice, mechanical, electromechanical, and a variety of magnetic and electrical tachometers have come into use, these devices measuring the instantaneous value of the number of revolutions. Tachometers for a range of 1000-20,000 rpm are used for tests of gas-turbine engines; some machines exhibit greater rpm; for example, the turbines of aircraft turbine-driven cooling units operate at speeds of up to 100,000 rpm. In the case of extremely high speeds [number of revolutions] the latter are reduced to magnitudes

which can be measured by industrially produced tachometers or they are measured by means of specially designed tachometers.

Counters indicate the total number of revolutions for a given time segment.

Counters

Counters are simple, reliable, and given constant engine rpm, they are extremely accurate. These counters record the number of shaft revolutions executed within a given time interval (1-2 min).

Figure 66 shows the diagram of a counter. The counting mechanism
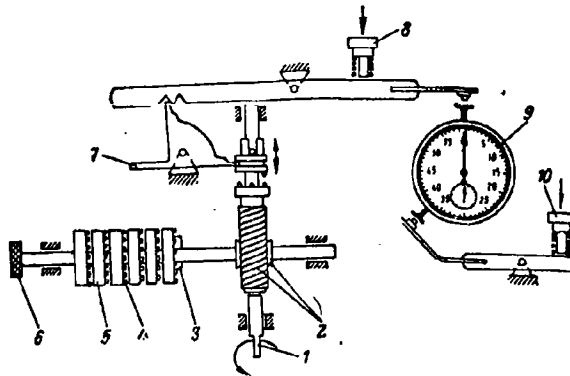
Fig. 66. Diagram of counter. 1) Drive shaft; 2) worm gear; 3) friction clutch; 4) disk pins; 5) counter disk; 6) counter reset dial; 7) lever to actuate counter; 8) auxiliary timer key; 9) timer; 10) button to reset hand of timer to zero position.

consists of a number of disks 5 with pins 4 that are connected to one another in series, the gear ratio in this case being 1/10. If the right-hand wheel executes 1000 revolutions, the wheel behind the first will execute 100 revolutions, the following wheel 10, etc. There are numerals on the surfaces of the disks and it thus becomes possible to read the number in the decimal system.

A worm gear is seated freely on shaft 1 and until this gear meshes

- 113 -

with the shaft the counter mechanism does not function. If lever 7 is raised upward, the downward movement of the sleeve links the worm gear with shaft 1 and actuates the counting mechanism. Timer 9 goes into action at the same time. The counter can be stopped by exerting force on lever 7. Button 10 resets the timer to the zero position, while button 8 is used to start the timer independently.

Electrical tachometers

Let us examine the operating principle and the structural elements of a magnetic-induction tachometer of the ITE-1 type (Fig. 67). With
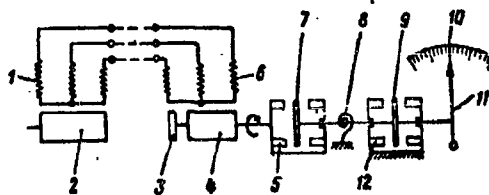
Fig. 67. Schematic circuit-diagram of the ITE-1 magnetic-induction tachometer. 1) Winding of sensing-element stator; 2) sensing-element rotor; 3) hysteretic disks; 4) rotor of meter; 5) six-pair magnet; 6) stator winding of synchronous motor; 7) sensing element; 8) spring; 9) aluminum disk; 10) scale; 11) pointer; 12) fixed magnets.

the turning of rotor 2 of the sensing element a three-phase current with a frequency proportional to the number of engine revolutions is excited in the winding of stator 1. The current is transmitted to the winding of stator 6 of the synchronous motor of the rpm counter over wires and it sets rotor 4 into motion.

A 12-pole six-pair magnet 5 is seated on the rotor shaft of the engine. A sensing element — disk 7 — is positioned between the poles of the magnet; eddy currents are induced in this element as a result of magnet rotation. The torque applied by the magnetic field to disk 7 is proportional to the revolutions of the engine. The spiral spring 8

balances the active moment; thus the number of revolutions is measured by the turn angle of pointer 11 and the value of the number of revolutions is read from scale 10 in absolute terms or in a percentage.

Magnetic braking is employed to settle the measuring system; an aluminum disk 9 is fastened between the fixed magnets 12 on the shaft of pointer 11 and eddy currents are induced in this disk. The interaction of the magnetic fields of the disk and the magnets leads to the appearance of the braking and damping moment.

Figure 68 shows a longitudinal cross section of the measuring unit of a tachometer. This measuring unit consists of two components: a synchronous motor and the measuring mechanism.

The synchronous motor consists of stator 17 and rotor 4 made in the form of two crossed magnets 5 and a starting element, i.e., three hysteretic disks 3 positioned on sleeve 2. The permanent magnets are freely positioned on the shaft and connected to the latter by means of spring 6 through which they transmit the torque to the engine shaft of the motor.

The magnetic unit 8 consists of two plates into which permanent magnets 9 have been pressed. The opposite poles of the magnets are located opposite each other and concentrate the magnetic flux about the outer edges of the sensing element (the disk) to derive the maximum moment of rotation. The measuring mechanism has a sensing element 10 positioned in the air space of the magnetic unit between the ends of the cylinder magnets.

Pointer 11 on scale 12 of the measuring unit shows the number of revolutions per minute of the engine shaft of an aircraft. The material of which the sensing element is made is an aluminum-manganese alloy exhibiting a low thermal coefficient of electrical resistance, as a result of which a change in temperature exerts little significant ef-
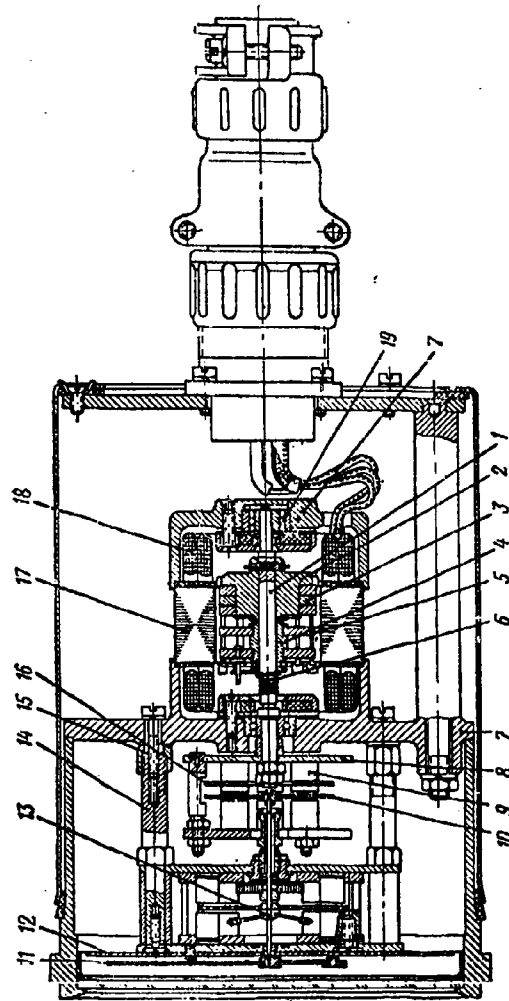
Fig. 68. ITE-1 measurement unit of the tachometer. 1) Shaft; 2) sleeve; 3) starter elements (hysteresis disks); 4) rotor; 5) crossed magnet; 6) spring; 7) cover; 8) magnetic unit; 9) permanent magnet; 10) sensing element; 11) pointer; 12) scale; 13) shaft; 14) support; 15) adjustment nuts; 16) shunt; 17) stator; 18) three-phase winding; 19) roller bearings.

fect on the readings of the instrument.

Temperature compensation in the measuring unit is achieved in the following manner; a magnetic shunt 16 made of a special alloy whose magnetic permeability diminishes with a rise in temperature and increases with a drop in temperature is positioned on magnets 9 of the magnetic unit. With the surrounding medium at a constant temperature the shunt draws a portion of the operating magnetic flux to itself and thus reduces the operating flow in the clearance between the ends of the magnets of the magnetic unit.

With an increase in temperature the operating magnetic flux in the clearance is increased, while with a drop in temperature the operating magnetic flux is reduced. A change in the operating magnetic flux in the clearance as a result of a change in magnetic permeability on the part of the shunt corresponds to a change in the electrical resistance of the sensing element which preserves the magnitude of the moment of system rotation produced by the magnetic unit virtually unchanged.

The sensing-element unit is fastened onto three supports 14 by means of adjustment nuts 15. There is a special magnetic unit in the instrument which provides a braking moment for the moving system, thus increasing the stability of the pointer.

The DTE-2 sensing element of the tachometer (Fig. 69), used in the place of the ITE-1 indicator, is a three-phase AC generator with a permanent four-pole magnet acting as the rotor. Rotor 2 is cast from ANK alloy which exhibits the property of high induction and a considerable coercive force. Stem 4 transmits the rotation of the aircraft-engine driveshaft to the sensing-element rotor.

Stator 1 is made of transformer-iron plates to reduce eddy-current losses. The stator plates are insulated from one another. The stator
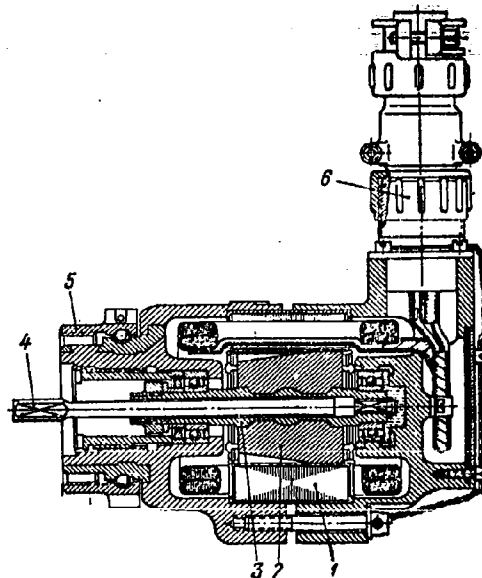
Fig. 69. DTE-2 tachometer sensing element. 1) Stator; 2) rotor (four-pole magnet); 3) shaft; 4) stem; 5) cap nut; 6) three-prong plug.

winding — four-pole and three-phase — is made of copper wires. Each phase of the stator winding has four coils. The phases are connected by means of a wye-connection and the assembly wiring from the measurement unit to the sensing element is connected by means of a three-prong plug 6. The sensing element is attached to the aircraft-engine drive by means of cap nut 5.

In addition to the DTE sensing element, the more exact standardized ferrodynamic test-stand TSFU-1 tachometer is also used. The current frequency of the sensing element is proportional to the number of aircraft-engine revolutions and is measured, in this case, by means of a frequency meter employing a resonant-compensation circuit (Fig. 70).

A compensation ferrodynamic AC ratiometer with a steel magnetic circuit 1 is used in the circuit for the measurement of frequency.
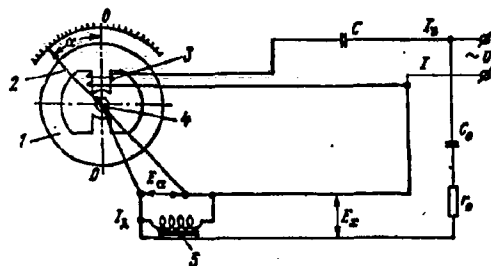
Fig. 70. Schematic circuit diagram
of resonance-compensation frequency
meter. 1) Yoke-magnetic circuit; 2)
pointer; 3) coil; 4) coil form; 5)
choke.

Coil 3 is wound about the projection of yoke 1. The movable coil form
4 can turn about a shaft, i.e., the steel core. Pointer 2 indicating
the number of revolutions is fastened to the movable form 4. Form 4
closes on choke 5. Upon passage of current through coil 3, a variable
magnetic flux is set up in the yoke and induces the emf E_α which re-
sults in the appearance of a current in the coil form 4. As a result
of the interaction of the yoke and coil-form fields a rotational moment
M appears and seeks to turn pointer 2 to the 00 position, which is sup-
ported by the induction of choke 5. The active moment appears as a re-
sult of the application of a variable voltage U and the appearance of
the emf E_x in the circuit with capacitor C_0 and the active resistance
r_0.

The fixed coil 3 is supplied from the same source of variable
voltage U through capacitor C. The current I_d of the form is a func-
tion of E_α induced in form 4 and it is also a function of E_x applied
to the form from the measuring circuit. The voltage at choke 5 func-
tions in the role of E_x.

The rotational moment of the ferrodynamic measuring mechanism is
a function of the magnitude of the form current I_d, of the magnetic
flux of Φ_3 of the fixed coil, and the angle of shift for the phases

- 119 -

between them:

$$M = k\Phi_s I_\text{A} \cdot \cos\varphi. \qquad\qquad (104)$$

The circuit is designed so that the induction of the fixed coil 3 and the capacitance of the series-connected capacitor C are in resonance when the mean value of the measured frequency in the given range of revolutions is attained.

The capacitance C_0 of the parallel circuit, the active resistance r_0 of the parallel circuit, the induction of choke 5, and the active resistance of form 4 are selected so that in the case of the mean frequency in the measured range of frequency the current I_d in the form will be shifted with respect to the flow Φ_3 of the fixed coil through an angle of 90°. Given such relationships, the moment of the form is equal to zero, the movable part is in equilibrium, and the pointer indicates the middle of the scale.

The resonance in the circuit of the fixed coil 3 is disrupted when frequency changes in any direction and the phase-shift angle φ of the frame current I_d is no longer equal to 90° with respect to the magnetic flux Φ_3. The moment M of the form in this case is no longer equal to zero and the form will deflect to the right or to the left from the central position until the phase-shift angle φ between the form current I_d and the magnetic flux Φ_3 of the fixed coil again becomes equal to 90°. The rotational moment again is equal to zero and the form remains in its new position of equilibrium which corresponds to the angle α. Because of the induction of choke 5 stable equilibrium of the moving part of the ratiometer is achieved in the form circuit.

A definite angle α of pointer deflection from the neutral position CO corresponds to each value of frequency within the limits of the given range. The instrument scale may be calibrated in fractions of revolutions, in whole revolutions, or in cycles per second.

The measuring device in the circuit described here exhibits good accuracy, and slight sensitivity to fluctuations in magnitude [amplitude] and shape of the sensing-element voltage.

Verification of tachometers and accuracy in the measurement of the number of revolutions

The influence of the errors in the measurement of the revolutions on the accuracy of determining thrust and specific fuel consumption for a single turbojet engine when n = 12,000 rpm is shown in Table 12 presented below.

TABLE 12

1 Погрешность изме-рения числа оборотов		2 Относительная ошибка в %	
3 абсолютная (об/мин)	4 относительная %	5 тяги	6 расхода топлива
10	0,083	0,38	0,32
20	0,167	0,80	0,63
40	0,333	1,57	1,27
80	0,667	3,13	2,60

1) Error in measuring the number of revolutions;
2) relative error, in %; 3) absolute (rpm); 4) relative, %; 5) thrust; 6) fuel flow rate.

The exact measurement of the number of revolutions can be achieved through the utilization of high-quality tachometers and by checking these on a regular basis. The tachometers are checked by comparing their readings with data from a control tachometer. Counters, precise watchwork tachometers, and quartz or tuning fork-tube frequency generators may be used as the control instrument.

One of the possible versions of an installation for the checking of tachometers is presented in Fig. 71. The installation consists of electric motor 5 which can be moved by means of handle 3 and friction gearing consisting of a small disk 2 and a large disk 1. The test and control tachometers 4 and 7 are connected to the shaft of the friction
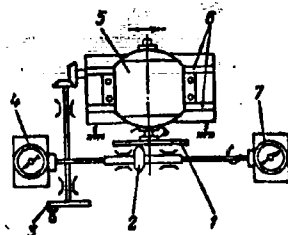
Fig. 71. Installation for checking of tachometers. 1) Large disk of friction gearing; 2) small friction-gearing disk; 3) handle to shift electric motor; 4) tachometer being tested; 5) electric motor; 6) electric-motor guides; 7) control tachometer.

gearing. The friction gearing makes it possible to change the revolutions of the tachometers smoothly within a given range. The accuracy of tachometer calibration depends on the precision of the control tachometer.

The accuracy of the counters is rather high, i.e., in measuring the number of revolutions within a period of 60 seconds, we find that the measurement error in the case of time amounts to 0.03-0.05 seconds, which yields an error in the case of a uniformly rotating engine shaft, of the order of $\pm 0.1\%$.

The accuracy of the ITE-1 and ITE-2 magnetic-induction tachometers is characterized by the data presented in Table 13.

TABLE 13

Accuracy of Magnetic-Induction ITE-1 and ITE-2 Tachometers as a Function of Temperature

1 Предел измерений %	2 Погрешность в % при температуре в °C		
	+20	+50	—60
10—60	±1,0	±1,5	±2,5
60—100	±0,5	±1,0	±1,5
100—105	±1,0	±1,5	±2,5

1) Measurement limits, in %; 2) error in %, at a temperature in °C.

The test-stand ferrodynamic tachometers of the FT-49 and the FT-49/13.5 type exhibit greater accuracy; the error of the FT-49 does not exceed $\pm 0.5\%$ while the error of the FT-49/13.5 does not exceed $\pm 0.35\%$. The test-stand TSFU-1 tachometer provides for extremely high accuracy in the measurement of numbers of revolutions (the measurement error does not exceed $\pm 0.2\%$).

7. MEASUREMENT OF RAPIDLY CHANGING QUANTITIES

Rapidly changing quantities in a VRD [ramjet engine] are measured by means of special sensing elements which convert nonelectrical parameters into electrical parameters whose change is determined by means of oscillographs. A record of rapidly changing revolutions is required for a study of transient engine responses. The measurement of rapidly changing pressures and temperatures makes it possible to study such important processes as surge and temperature fluctuations.

Engine balance is one of the most important indices of the operational suitability of an engine. Balance can be evaluated by recording the frequency and amplitude of frame vibrations. The recording of compressor and turbine component vibrations aids in the determination of engine resonance regimes and serves to eliminate the breaking of component parts due to vibrations.

Below we will examine the construction of the oscillographs and sensing elements for the recording of vibrations, revolutions, and rapidly changing pressures and temperatures.

Oscillographs for the recording of rapidly changing processes

Magnetic-electric (loop) and electron (cathode-ray) oscillographs are used.

Figure 72 shows the diagram of a loop (or vibrator) magnetic-electric oscillograph. The loop consists of a permanent magnet 4 in whose field there is a current-conducting loop 1 to which tension is applied by means of spring 5 and which is connected to two insulating prisms 2. Mirror 3 is glued to the loop. If a current of variable amplitude passes through the loop, the mirror will begin to vibrate as a result of the interaction between the fields of the loop and the magnet and the incident beam on the mirror will be deflected. To damp the vibrations after the disappearance of the exciting pulses, this system

is immersed in oil. The frequency of oscillations recorded by such loops does not exceed 10,000 cps.

Figure 73 shows the diagram of the optical system of a loop oscillograph. A beam of light from lamp 1 passes through condenser 2 and diaphragm 3; this beam is directed to the mirror 10 of the loop by means of a refraction prism 4.

Because of the variable current passing through the loop, the mirror begins to oscillate and the beam of light to the deflected prism 9 also oscillates. The portion of the beam passing through the deflected prism 9 impinges on the rotating facets of the mirror drum 8. Because drum 8 is faceted we achieve a time sweep of the beam and it becomes possible to observe the curve of the process on ground-glass screen 5.
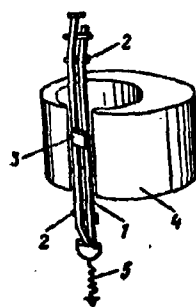
Fig. 72. Magnetic-electric loop oscillograph. 1) Loop; 2) support prism; 3) mirror; 4) magnet; 5) tension spring.
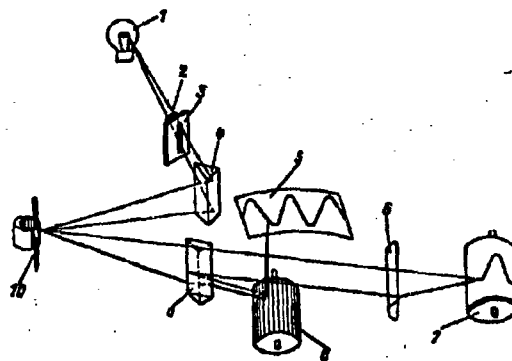
Fig. 73. Diagram of loop oscillograph. 1) Light source; 2) condenser; 3) diaphragm; 4) refraction prism; 5) ground-glass screen; 6) cylindrical lens; 7) drum with photographic paper; 8) faceted mirror drum; 9) deflecting prism; 10) loop.

The portion of the beam passing beneath the prism 9 through the cylindrical lens 6 impinges on the rotating drum 7 which is covered with photographic paper. In addition to the curve of the process, a sinusoidal curve whose period of oscillation is known exactly (for ex-
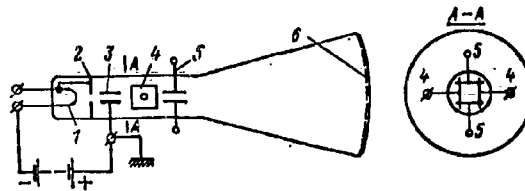
Fig. 74. Diagram of cathode-ray oscillograph. 1) Cathode; 2) diaphragm; 3) anode; 4, 5) deflecting plate; 6) screen.

ample, 500 cps) is recorded on the photographic paper. This curve is produced by one of the loops of the oscillograph known as the time marker. The time-marker curve is also projected to the ground-glass screen 5.

The general-purpose [universal] eight-loop magnetic-electric portable MPO-2 oscillograph has gained widespread acceptance in our industry. It is operationally convenient and exhibits small dimensions and weight. The optical recording of the processes in this device is achieved by means of a 35-mm wide film strip which is passed through the unit at a speed of 5 m/sec. Thanks to the great sensitivity of the film strip, an electric lamp of only 7.5 w is used as the light source in the MPO-2.

Electron [cathode-ray] oscillographs (Fig. 74) are used for the recording of high-frequency oscillations. The heated cathode 1 emits electrons which pass through the slit in diaphragm 2 and are scattered by the electric field of plate 3; the narrow bundle of electrons passes between the vertical and horizontal deflecting plates 4 and 5. Each of the plate pairs is provided with insulated leads from the tube. One of the plate pairs is connected to a voltage changing according to a definite law, e.g., a linear law. The voltage being tested is applied to the second plate pair. Under the action of the plate fields the beam describes a curve on screen 6 that is covered with a fluorescent com-

- 125 -

position. The curve can be photographed by means of a camera attachment for purposes of later study.

Measurement of engine vibrations

Vibrations are recorded during tests of full-scale engines. The instruments used for the measurement of vibrations are known as vibrographs. They consist of sensing elements, integration-differentiation amplifiers, and an indicator. Thus, for example, there are 6 sensing elements in the AV-42 vibrograph (4 horizontal and 2 vertical sensing elements), 3 integration-differentiation amplifiers, a control panel, and connection hoses. The readings of the vibrograph can be recorded on any loop oscillograph.

Let us restrict our examination to the construction of the vibrograph sensing element (Fig. 75). Shaft 8 keeps heavy magnet 4 in bearings 6 that are kept in place by covers 1; the heavy magnet can move freely along the frame.

Springs 2 and 5 represent elastic supports for the magnet. The natural frequency of the spring-magnet system is significantly lower than the vibrational frequency of the engine or unit being tested; therefore, the magnet remains fixed in position (along the axis) in the case of engine vibration, while the housing of the sensing element, fastened by flange 9 to the engine, is set into vibration. The magnetic flux passes through the clearances and closes on the iron housing of the sensing element. A magnet is inserted inside coil 3 with a winding, one end of which leads out to clamp 7 while the other is connected to the sensing-element housing.

As a result of the motion of the sensing-element and coil housings with respect to the magnet, an emf is induced in the coil and the magnitude of this force is determined from the following formula:

$$E - cv, \qquad (105)$$
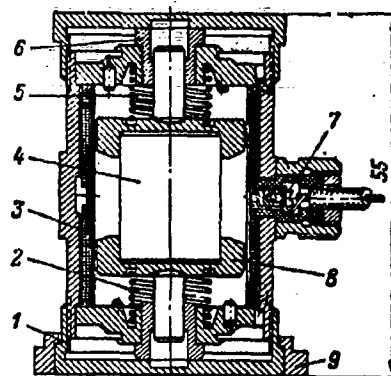
Fig. 75. Vibrograph sensing
element. 1) Cover; 2, 5)
springs; 3) coil; 4) magnet;
6) bearing; 7) clamp; 8) mag-
net shaft; 9) flange.

where E is the emf, in mv; c is a coefficient, in mv·sec/mm; v is the
speed of the relative motion, in mm/sec.

The sensitivity of the sensing element is determined from the fol-
lowing formula:

$$K = E/fs, \tag{106}$$

where s is the vibration amplitude, in mm; f is the vibration fre-
quency, in cps.

Since the change in emf is proportional to the speed of the rela-
tive motion of the housing and the magnet, an emf differentiation and
integration circuit is incorporated in the amplifier; integration
yields the shift curve, while differentiation yields the acceleration.

The vibrograph normally functions at a vibration frequency of 20
to 300 cps; the acceleration amplitude is 0.5-10.0 g; the velocity amp-
litude is 10-375 mm/sec, and the amplitude of the shift is 0.02-1.5 mm.

Measurement of rapidly changing numbers of revolutions

An oscillograph can be used as a revolutions counter and it may
also be employed to record the instantaneous angular-velocity values.

- 127 -
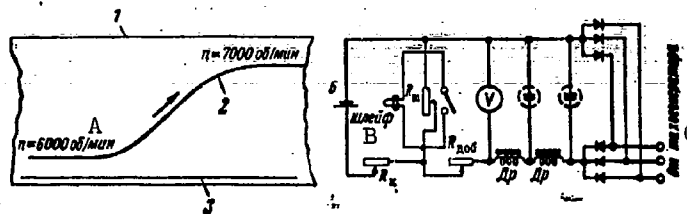
Fig. 76. Diagram of the recording of the instantaneous values of angular velocity and a specimen of the oscillogram. 1) Oscillogram; 2) curve of the number of revolutions; 3) base line. A) rpm; B) loop; C) from the speed-voltage generator.

Figure 76 shows the circuit diagram for the recording of the instantaneous values of angular velocity and a specimen of an oscillogram. The voltage of the three-phase speed-voltage generator is applied to a selenium rectifier. A filter is connected into the circuit to smooth pulsations.

The rectified constant voltage V is supplied through the extra resistance R_{dob} to the shunted (R_{sh}) loop of the oscillograph. To increase sensitivity, the circuit is provided with a compensation loop which includes battery $\underline{\underline{B}}$ and resistance R_k. The currents of source $\underline{\underline{B}}$ and the speed-voltage generator are subtracted from one another; with a change in the number of revolutions the difference between the currents changes and this causes the loop of the oscillograph to deflect.

Measurement of rapidly changing pressures

Two groups of sensing elements are used for the measurement of rapidly changing pressures:

1) sensors whose sensing element consists of a flexible membrane;

2) sensors whose sensing element changes its physical properties under the influence of the changing pressure.

The first group includes capacitance sensing elements, measuring devices with wire strain gauges, induction sensors, ion-mechanical sensing elements, optical-diaphragm devices, and magnetic-compensation

sensing elements.

The second group includes piezoelectric sensing elements, magneto-strictive sensors, electrokinetic units, radioactive-ionized sensors, and carbon sensing elements.

The operating principle of these sensing elements can be studied in detail in the book by G.P. Katys.* Let us examine the operating principle of the most frequently used induction and piezoquartz sensing elements.
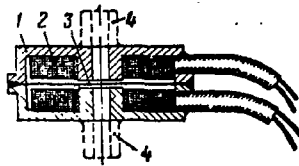
Fig. 77. Pressure pickup with induction sensing element. 1) Permalloy magnetic wire; 2) winding; 3) diaphragm; 4) connection tube for application of pressure.

Figure 77 shows a pressure pickup with an induction sensing element. Under the action of the pressure difference membrane 3 in this sensing element is bent. The equilibrium of the bridge into which this sensing element has been connected is disrupted as a result of the bending and this disruption is recorded finally on the oscillograph.

A sensing element of this type can be used for the recording of various pressure differences, depending on the thickness of the diaphragm. Thus, for example, if the diaphragm is 0.025 mm thick, it is possible to measure a difference ranging from 0 to 0.05 kg/cm^2; if the diaphragm is 0.20 mm thick, the range of differences that can be measured extends from 0 to 5 kg/cm^2. Because of the small dimensions of the cavities, distortions in the measured differences do not exceed 10% below frequencies of 400 cps. The weight of the sensing element is negligible and it can be made to very small dimensions.

Figure 78 shows a piezoquartz sensing element for the measurement of rapidly changing high pressures (of the order of several tens of atmospheres). This sensing element is included in the piezoquartz indicator.
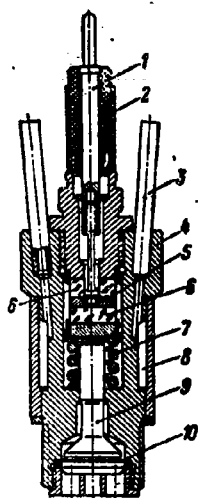
Fig. 78. Piezoquartz
sensing element for
the measurement of
rapidly changing
pressures. 1) Insu-
lated lead; 2) insu-
lator; 3) water-
cooling tube; 4)
sensing-element hous-
ing; 5) insulated
electrode; 6) quartz
plate; 7) spring for
preliminary compres-
sion of column of
quartz plate; 8)
cooling cavity; 9)
mushroom-shaped rod
for transmission of
force to quartz
plate; 10) sealing
membrane.

Fig. 79. Schematic circuit-diagram
of piezoelectric indicator. 1)
Piezoquartz plate; 2) piezoquartz
sensing element; 3) capacitor; 4)
electrometer tube; 5) amplifier
tube; 6) oscillograph loop.

Quartz plates 6 with the insulated slip
ring 5 pressed between the plates represent
an important element of the sensing unit. The
variable gas pressure is transmitted through
a sealing membrane 10 and a mushroom-shaped
rod 9 to the piezoquartz plates that convert
the work of the pressure forces into electric
power. To prevent the sensing element from
overheating, it is cooled with water.

Figure 79 shows one of the possible ver-
sions of a piezoquartz indicator. The piezo-
quartz plates are positioned so that the elec-
trical charges that form as a result of the
compression of these plates exhibit a single
sign (minus), these charges being removed by the slip ring. The posi-
tive charges are taken up by the mass. The magnitude of the formed
charges is proportional to the active forces. Thus the measurement of
forces in such indicators involves the measurement of electrical
charges.

An electron voltmeter is used as the device to measure charges.
The charge from the quartz plates 1 is applied to capacitor 3 and the

control grid of the electrometer tube 4. As a result of the established potential there is a change in the plate current of the tube, and it should be possible, in principle, to measure this current by means of a galvanometer. The current will be proportional to the force acting on the quartz plates. The current of tube 4 is somewhat too weak and it is therefore amplified by means of tube 5.

Loop 6 of the oscillograph is connected into the plate circuit of tube 5. A battery for the compensation of the null current of the amplifier is connected in parallel to loop 6 through the controlled resistance R_4. Piezoquartz indicators are used on a wide scale in the investigation of pressure fluctuations.

A shortcoming of the piezoquartz sensing elements is the fact that the magnitude of the piezoeffect is a function of temperature. At a temperature of $570^{\circ}C$ the quartz completely loses its property of being able to develop electrical charges under pressure.

Accuracy in the measurement of rapidly changing quantities

It is extremely complicated to determine the accuracy with which rapidly changing quantities are measured. The AV-42 vibrograph described earlier yields a basic error in the determination of any vibration parameter without the $\pm 10\%$ decoding error in the frequency range between 25-300 cps and the $\pm 15\%$ in the frequency range between 20-25 cps having been taken into consideration.

The error in the measurement of the angular variable velocity is composed of the time-marker error and the decoding of the oscillograms. Decoding accuracy can be increased by speeding up the speed with which the photographic paper is fed through the device. The error in the case of loops employing oil damping approaches $\pm 3\%$, while in the case of electromagnetic damping the error approaches $\pm 1.5\%$.

The error in the measurement devices used for rapidly changing

pressures has been estimated at 5-7% and consists of the sensing-element errors, and those of the amplifier and the oscillograph.

8. MEASUREMENT OF VIBRATIONS AND TEMPERATURES IN ROTATING COMPONENT PARTS

We have developed a number of methods for the measurement of vibrations and temperatures in rotating component parts. Thus, for the recording of vibrations we use capacitance and strain-gauge sensing elements, carbon-type sensing elements, etc. Thermocouples, a measurement method involving the hardness scale, fusible plates, thermocolors, etc., are used for the measurement of component-part temperatures. Let us examine the widely used method of measuring vibrations by means of strain gauges and the method of measuring the temperatures of rotating component parts by means of thermocouples.

Measurement of vibrations by means of strain gauges

The measurement of vibrations by means of strain gauges is based on the exploitation of the properties of certain metals noticeably to change their ohmic resistance in the case of deformation. Constantan, nichrome, manganin, chromel, etc., are used as the strain-gauge materials. Wires 0.01-0.03 mm in diameter are generally used in strain gauges. The wire is pasted in between strips of thin paper in the form of flat loops, as shown in Fig. 80. The strain gauges are attached to the component part being tested and the gauge is deformed together with the part.

With deformation of Δl mm the resistance of the strain gauge changes in accordance with the following law:

$$\Delta R = kR \frac{\Delta l}{l},\qquad (107)$$

where ΔR is the change in wire resistance; $\underline{k}$ is the coefficient of sensitivity to deformation; R is the initial resistance; l is the length of the wire at null voltage.
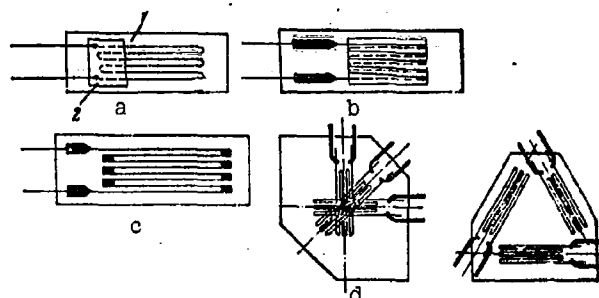
Fig. 80. Types of strain gauges. a) Strain gauge for a base of 5-25 mm; 1) bottom paper layer; 2) top paper layer; b) strain gauge for 5 mm base and lower, with spiral winding; c) foil strain gauge with lower coefficient of transverse strain sensitivity; d) strain gauges for study of complex stressed state.
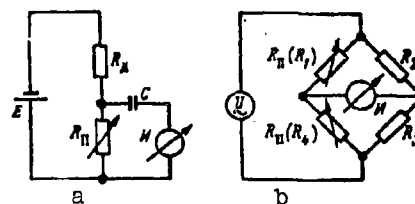
Fig. 81. Circuits for the inclusion of strain gauges. a) Circuit showing connection of potentiometer; R_d) resistance; R_p) strain gauge; C) capacitor; I) measuring unit (electron oscillograph); b) single-bridge circuit; R_2R_3) resistances; R_1 and R_4) strain gauges.

The accuracy of measurements carried out by means of strain gauges is primarily a function of their quality and the quality of the gluing process. The surface of the component part is machined to a finish of no less than ∇6; the machining striations must be perpendicular to the loops of the sensing element. Celluloid, carbinol, bakelite, bakelite-phenol (BF-2, BF-4), etc., are the types of glues used for the gluing process.

The strain gauges are connected to the measuring system by means of wires, and the system is generally set up in the form of a potentiometer or single-bridge circuit.

The potentiometer connection circuit (Fig. 81a) is used when only the variable component of resistance is of interest. The constant resistance component is filtered out at the transducer R_p by capacitor C. An oscillograph is generally used as the measuring unit $\underline{I}$.
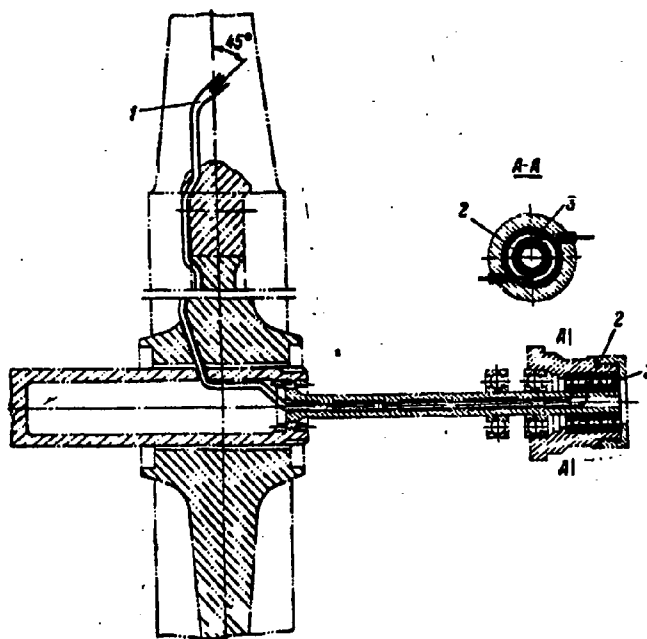
Fig. 82. Position of strain gauge on blade and diagram of connection between strain gauge and slip ring. 1) Strain gauge; 2) silver-coated electrically insulated rings; 3) wipers.

The single-bridge circuit (Fig. 81b) is used considerably more frequently, and the operating transducers are connected into one or two arms of the bridge. For dynamic measurements an unbalanced-bridge circuit is generally used. In this case, the measurement is carried out directly on the basis of readings from the measuring unit $\underline{I}$ con-

- 134 -

nected into the bridge diagonal.

Since the change in the strain-gauge resistance is very small, particular attention must be devoted to offsetting the change of this resistance due to fluctuations in temperature; we should also devote particular attention to the influence exerted by the difference between the expansion coefficients of the component part being tested and the material of the strain gauge. The influence of temperature on the measurement accuracy may be considerably reduced by the incorporation of a special compensation sensing element into the adjacent arm of the bridge (on the opposite side of the measuring diagonal), the identical temperature conditions being provided for this compensation sensing element as for the basic sensing element.

Figure 82 shows an example of the attachment of a strain gauge to a compressor blade. The transmission of current to the strain gauge and away from the strain gauge is a difficult problem when the current itself and the current oscillations are insignificant. In the case under consideration this problem is resolved in the following manner.

A wire from strain-gauge 1 is connected to the electrically insulated silver-coated rings 2 of the slip-ring armature; the fixed wipers 3 made of a constantan wire 0.2 mm in diameter slide over these rings. Wipers 3 are pressed to rings 2 by elastic force and it provides for excellent removal of current with negligible ring wear.

Measurement of component-part temperatures

The measurement of the temperature of fixed component parts generally presents no particular difficulty. The thermocouple is mounted in the component part and the leads from the latter are, if at all possible, carried away over isothermal surfaces (to reduce the transfer of heat from the thermocouple bead). The problem of measuring the temperature of rapidly rotating component parts such as, for example, tur-

- 135 -
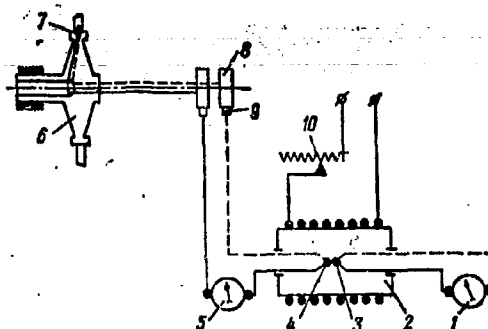
Fig. 83. Circuit for the measurement
of temperature by means of the com-
pensation method. 1) Millivoltmeter
of fixed thermocouple; 2) thermostat;
3) junction of fixed thermocouple;
4) hot junction of rotating thermo-
couple; 5) null indicator; 6) tur-
bine rotor; 7) hot junction of rotat-
ing thermocouple (mounted on compo-
nent part); 8) contact disks; 9)
sliding pressure contact; 10) rheo-
stat.

bine blades and disks, is considerably more complex.

Let us examine a method of measuring the temperatures of turbine
blades by means of the compensation method with the use of thermo-
couples; this procedure is shown in Fig. 83. Hot junction 7 of the
thermocouple is attached to the blade. The wires are carried over the
turbine disk and the shaft to disks 8 which carries contacts made of
silver. Steatite tubes are used to insulate the wires. The wires are
soldered to the disks.

The contact disks 8 transmit the current to the sliding contacts
9 made of constantan wire. The current of the measuring thermocouple
is balanced by the current of cold junction 4 in thermostat 2. The tem-
perature of the thermostat is measured by means of a fixed thermocouple
3. At the instant the temperature of the junction 7 and the junction 4
are equal, a highly sensitive mirror galvanometer 5 indicates the null
current.

An advantage of the compensation method is the considerable reduction in the role played by the contact resistances in the circuit and the measurement accuracy is therefore increased. A shortcoming of this method involves the length of time required to carry out experiments because of the thermal lag of the thermostat.

Manuscript Page No.	[Footnotes]
35	The collection "Physical Methods of Measurement in Gasdynamics and in Combustion," the translation edited by Yu.F. Dityakina, IL [Foreign Literature Press], 1957.
130	G.P. Katys. Methods and Instruments for the Measurement of Parameters in Nonsteady-State Thermal Processes, Mashgiz [Machine Industry Press], 1959.

Manuscript Page No.	[List of Transliterated Symbols]
37	к = k = kapillyarnost' = capillarity
56	в = v = verkhnyaya = upper
56	c = s = sreda = medium
62	cp = sr = sreda = medium
70	НП = NP = nulevoy pribor = null indicator
70	т = t = termopara = thermocouple
70	н = n = normal'nyy [element] = normal [element]
75	к = k = konduktsiya = conduction
76	л = l = luchistyy = radiative
81	кр = kr = kriticheskaya [skorost'] = critical [speed]
83	п = p = pribor = instrument
90	ш = sh = sherokhovatost' = roughness
90	к = k = kromka = edge
97	п = p = poplavok = float
97	т = t = toplivo = fuel

[List of Transliterated Symbols (Continued)]

109   ИКМ = IKM = izmeriteli krutyashchego momenta = torquemeters

109   ТВД = TVD = turbovintovoy dvigatel' = turboprop engine

126   МПО = MPO = magnitoelektricheskiy perenosnyy ostsillograf =
                = magnetic-electric portable oscillograph

129   доб = dob = dobavochnoye = extra

129   ш = sh = shunt = shunt

129   к = k = kompensiruyushchiy = compensating

Chapter 4

A LABORATORY FOR TESTING OF ENGINES, AND THEIR UNITS AND COMPONENTS

Laboratories are set up in conjunction with the experimental design offices of factories as well as at scientific-research and educational institutes.

It is the primary function of these factory laboratories to determine the operating cycle and strength of the units and elements of those engines on which the given factory or group of factories is working.

Scientific-research work in the field of engine and engine-component cycles is conducted in the laboratories of the institutes; in addition, these laboratories are engaged in a thorough study of engine and engine-component characteristics.

A system of scientific-research institutes generally has high-altitude installations at its disposal for the testing of full-scale engines.

1. GENERAL INFORMATION ON LABORATORY EQUIPMENT

The following basic requirements are imposed on the testing laboratories:

1) the laboratory equipment must be capable of carrying out the assignment of the laboratory;

2) the measurement systems must provide for accurate and rapid recording of the required quantities;

3) laboratories must have all forms of power supply at their dis-

posal;

4) the products of the combustion of fuels and the waste liquids must not be permitted to contaminate the surrounding area;

5) the testing installations must be provided with noise-absorbing devices.

Let us examine the power systems and the basic laboratory equipment.

The air system

The air systems of these installations are more complex than analogous systems encountered at factory testing stations, particularly in the case of simulating flight conditions.
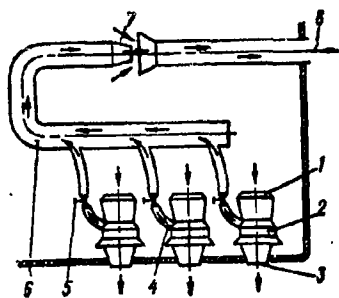
Fig. 84. Diagram of air-blower device, with removal of air behind the compressors of the turbojet engines. 1) Air inlet to TRD [turbojet engine]; 2) TRD [turbojet engine]; 3) ejection of gases from TRD; 4) removal of air behind compressor; 5) throttle valve; 6) air manifold; 7) ejector device; 8) supply of air to testing station.

In order to achieve the required velocity and pressure at the inlet to the engine the air is compressed in special compressor devices in which it is heated or cooled by means of heat-exchange equipment; in addition, the air is either dried or made more moist. In installations which are operated only for short periods of time the air is first pumped by means of a compressor into receivers (tanks), subsequently supplied to the engine during the period of the test. In the case of installations intended for prolonged testing, the air is supplied to the engine from the compressor which achieves the required air flow rate and pressure.

Centrifugal or axial compressors operated by electric motors, steam turbines, or gas turbines, are used to compress the air. Piston

- 140 -
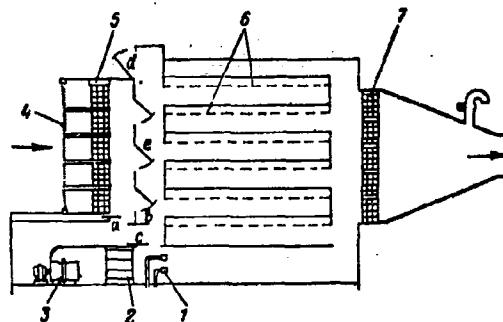
Fig. 85. Diagram of air dryer. 1) Pre-
heater burners; 2) air cooler; 3) fan;
4) inlet grid; 5) primary filter; 6)
dryer sections; 7) secondary filter.

compressors are used in those cases in which it is necessary to have a
comparatively small quantity of air at high pressure (for example, in
the case of intermittent installations with receivers).

Such other methods as the use of series-produced TRD [turbojet
engines] in which a portion of the air is taken directly behind the
supercharger and supplied to the general air system feeding the engine
can be employed in order to achieve the required air velocity at the
inlet to the engine. The advantage of using a series-produced turbojet
engine to obtain air exhibiting comparatively high parameters can be
explained by the fact that the resultant installation is compact,
since it combines into a single unit the source of power — a turbine,
or more accurately, a source of air — a compressor, and all of the re-
quired power, cooling, and control elements.

In the most common air-blower design, based on the utilization of
a TRD [turbojet engine] (Fig. 84), the reduction in the quantity of
gas passing through the turbine of the engine is offset by expanding
the exhaust nozzle. Thus the turbine is made to operate at elevated
pressure differences in comparison with the rated [theoretical] differ-
ences. To increase the service life of the engine that is being used

as the air blower the temperature of the gases in front of the turbine should be kept, if at all possible, within the following limits: $T*_3 =$ $= 800-850°K$. To increase the mass of air, an ejector may be incorporated into the system, but this will result in a loss of total pressure.

To prevent the formation of a condensate or "snow" in the air-supply system, the air is dried. Silica gel, alumogel, and activated bauxite are employed as the moisture absorbents. Figure 85 shows a diagram of such a drying installation. During the operation the valves a, b, and d are closed and the air passes through filters 5 and 7 and drying sections 6 into the channel. After the dryer has become saturated with moisture, valves b, c, and e are closed for purposes of regeneration. The air is drawn by means of fan 3 through inlet grids 4 as part of the regeneration of the moisture absorbent; fuel is burned in [special] chambers to heat the air which is then passed through the dryer sections 6 and passed out through valve d. The cooling installation 2 is shut down during this period.

Depending on the nature of the test being conducted, the incoming air to the engine must either be heated or cooled.

Great quantities of air are heated by burning fuel or through the use of heat-storage devices. In the former case, the air is contaminated with products of combustion and this is reflected in the functioning of the object being tested. Figure 86 shows a portion of a heat-storage device consisting of steel matrices having a total weight of 36 tons which are heated by means of electric heaters requiring a power of 1500 kw. The storage unit is divided into three lengthwise sections; the valves between these sections make it possible, through the use of pneumatic regulators, to maintain a given temperature at the outlet from each section. Special heat controls restrict the max-

imum matrix temperatures.

Electrical heating during engine tests under natural conditions is economically unsound because of the great expenditures of electrical energy (more than 25 thousand kilowatts are needed to heat 50 kg/sec of air to 540°). The majority of installations for the testing of VRD [air-breathing engines] under natural conditions function with heaters in which hydrocarbon fuels are burned (gas, kerosene, petroleum).
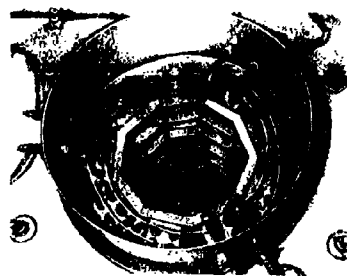
Fig. 86. A portion of the matrix heat-storage unit.

Turbine-driven compressed-air machines consisting of a turbine whose power is absorbed by means of brakes are used to reduce the temperature of the air entering the engine. A centrifugal impeller drawing air from the atmosphere functions as such a brake. Freon refrigeration equipment is used to cool the air. In this case, the air is cooled in a heat exchanger through which freon vapors circulate. The pressure of the air entering the engine is controlled by means of throttles and bypass valves.

The dimensions of the air manifolds must be adequate to carry the rated [theoretical] quantities of air for the permissible pressure losses.

A serious problem in designing an air manifold is the adaptation of same to a wide range of air flow rates. It is virtually impossible rapidly to change air pressure and temperature in the case of low flow rates in tubing designed for a substantially greater flow rate. This pertains to a significant degree to air heaters. Hence follows the conclusion that installations for engine tests must be equipped with several air-supply systems originating from receivers or compressor sta-

tions.

The exhaust system

To reduce gas pressures in order to simulate high-altitude conditions, a system of preliminary gas cooling and removal is installed at the exhaust of the test installation. The gases may be removed by means of exhausters operated by electric motors or turbines. Series-produced turbojet-engine exhausters may be used. In some cases it is also possible to use multistage steam ejectors supplied with steam from accumulators [storage devices] charged by boilers.

The cooling of the exhaust gases may be carried out in heat exchangers (water serving as the coolant), or by the injection of water into the gas stream. The injection system is simpler and more expedient, since it reduces to a minimum the danger of the explosions that are possible during the starting or sudden stopping of the engine being tested. Occasionally both methods are employed simultaneously.

The fuel system

The fuel systems of the laboratories are marked by their universality, by the extensive possibilities of controlling the flow, pressure, and temperature of the fuel at the inlet to the engine, and also by the great quantity of monitoring-measuring instruments. Two independent fuel systems are necessary to simulate high-altitude conditions. The fuel tank of the first system is situated outside of the heat-pressure chamber, while the fuel tank of the second system is contained within the heat-pressure chamber, thus making it possible to change the pressure and temperature of the fuel in the tank.

Auxiliary systems

Pumping stations providing for the supply of great quantities of water to cool the installations, the exhaust gases, the fuel, etc., must be included among the auxiliary equipment of a laboratory. Exist-

ing pumping stations at high-altitude laboratories provide a water feed of up to 25 m^3/min for purposes of testing air-reaction engines. In the case of high flow rates the water is cooled by means of cooling towers or pools from which the water is returned to the laboratory.

Electric-power distribution systems are of great significance for a laboratory. AC electric motors, dynamotors, DC generators, current transformers, frequency converters, etc., are included as part of the electrical equipment of a laboratory. The total power of the spent electrical power is measured in tens of thousands of kilowatts. The electrical system of the laboratory must provide for the operation of both AC and DC instruments operating at various voltages.

The complexity of the research, the cumbersome installations, the requirements of safety measures, and the great number of measurements (perhaps as many as several hundred) carried out during the course of the experiments within a short period of time, bring forth the necessity of providing for remote control, and the observation and recording of parameters. Observation is carried out directly through special windows or by means of television installations. It is best to employ automatic devices for purposes of the recording.

The instrument readings can be transferred automatically to the electric computers that analyze the results. Such systems can take calibration into consideration and provide for the instantaneous printout of test results. The entire measurement cycle and the evaluation of these data for the given conditions requires approximately 1 minute. For installations of short operating duration this is a long time. Automatic measuring systems with storage of the derived data are used successfully in such installations. The input readings of the instruments in such systems are converted into digital signals and recorded on magnetic tape. Upon completion of the test the tape is passed
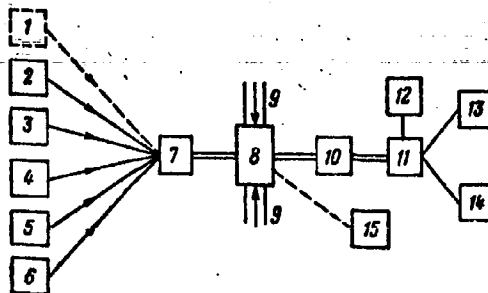
Fig. 87. Block diagram of control
system. 1) Analog-digital converter
for transient operations; Measure-
ment converters: 2) of pressures; 3)
of temperature; 4) of rpm; 5) of
fuel flow rate; 6) of thrust; 7)
data-evaluation unit; 8) connection
box; 9) input of digital data from
other cells; 10) memory [storage]
device; 11) computer; 12) manual con-
trol position; 13) tabulating ma-
chine; 14) automatic instrument for
plotting of curves; 15) electro-
mechanical data indicator.

through the corresponding converter which produces punch cards that
are then processed through computers.

Figure 87 shows one of the possible test and measurement-recording
control circuits. The readings of the instruments are wire-transmitted
to a central equipment room. The signals are coded in this central
equipment room and all of the information is transmitted to a control
center from which it is directed to a storage unit. The data are re-
corded or plotted automatically after the computer analysis. If neces-
sary, some data may be analyzed and automatically plotted individually
during the course of the tests for purposes of control.

2. LABORATORIES FOR HIGH-ALTITUDE ENGINE TESTS

The recording of altitude and velocity engine characteristics on
the ground calls for special complex equipment and enclosures espe-
cially adapted for these purposes, i.e., high-altitude laboratories in
which the following problems are resolved:

- 146 -

Fig. 88. Diagram of high-altitude installation.
1) Compressor; 2, 6, 14, 18) heat exchangers; 3)
air dryer; 4, 8) turbine-driven compressed-air
machines; 5, 7) air brakes; 9) metering nozzles;
10) air heater; 11) combustion-chamber testing
installation; 12) heat-pressure chamber; 13) dif-
fuser; 15) heater; 16, 19) spray-nozzle injector
cooling devices; 17, 20) exhausters. a, b, c, d,
e, f, g) Valves.

1) the recording of altitude-velocity engine characteristics;

2) the determination of surge-regime regions and the selection of
operational regimes;

3) verification of engine restart capabilities at various alti-
tudes and at various flight speeds;

4) investigation of combustion processes under high-altitude con-
ditions;

5) determination of influence of climatic conditions on engine
operation, etc.

In order to simulate the operating conditions of an engine in
flight on a test stand it is necessary to provide for the control of
the pressure, temperature, and moisture content of the air entering
the engine and the heat-pressure chamber, as well as to control the
pressure at the exhaust. In recording characteristics in which external
drag plays a role it is necessary to provide for the corresponding con-
ditions of flow past the engine.

The diagram of one such high-altitude installation is shown in

Fig. 88. This installation makes it possible to conduct research on the cycle of a full-scale engine as well as on the combustion processes in individual [combustion] chambers to altitudes of H = 15 km.

The air having passed through the filter enters a two-cascade centrifugal compressor 1 that is set into motion by means of an electric motor. Refrigeration units are installed between the cascades and behind the compressor. The temperature of the air at the outlet from the compressor may be of the order of $300^\circ C$, the pressure will be of the order of 5.6 atm abs, and the air flow rate is constant and equal to 3.17 kg/sec; the air flow rate is regulated by means of bypass valves. The air enters a tubular heat exchanger 2 from the compressor.

The air subsequently passes into the air dryer 3 consisting of two pairs of standard sections operating on activated aluminum oxide, these sections operating alternatingly. After the air dryer the air enters the turbine-driven compressed-air machine 4 whose power is absorbed by air brake 5 (the centrifugal compressor). The temperature of the air increases at the outlet from the heat exchanger 6. The working temperature of the air is achieved by means of a second turbine-driven compressed-air machine 8 in which the temperature can be reduced to $-100^\circ C$, while the pressure can be reduced approximately to 1.05 atm. The required temperature is set by means of the bypass valve b. The air branches out behind the turbine-driven compressed-air machine. The portion of the air moving to the test stand enters a group of metering nozzles 9 that are connected in parallel and vary in diameter, thus making it possible to carry out exact measurements within a wide range of air flow rates.

The electric air heater 10 fitted out with a plate temperature stabilizer is positioned behind the metering nozzles. Passing through the heater, the air is directed either to the combustion-chamber test-

ing installation 11 or to the heat-pressure chamber 12.

The heat-pressure chamber has an inside diameter of about 4 m and it exhibits a length of 12 m. The air-inlet side of the chamber is demountable, this being necessary in order to install and remove the engine being tested. Access to the engine during the intervals between tests is achieved through a hatch in the side wall. The chamber is covered on the outside with a heat-insulation layer. The air inside the chamber is carried directly to the engine inlet.

Turbojet-engine thrust is determined either by calculation on the basis of exhaust-gas parameter measurements or by means of a dynamometric device. The power of turboprop engines is absorbed by means of a hydraulic brake mounted inside the chamber.

Fuel is supplied from a tank situated inside the heat-pressure chamber through a number of heat exchangers, thus making it possible to control the temperature of the fuel. The fuel tank is kept under pressure, the magnitude of which changes as a function of the "altitude" in the chamber. The exhaust nozzle of the engine is connected to diffuser 13, thus making it possible to raise the "altitude" of the chamber. The diffuser is cooled by means of water, as is the exhaust tube (connected to and inside the diffuser) of the combustion-chamber testing installation.

The gases leave the diffuser and enter the tubular water-cooled heat exchanger 14 in which, if necessary, the gases can be cooled; then they pass onto heater 15 and through valve f, which serves as an "altitude" control, to the spray-nozzle cooling device 16 which consists of a number of spray nozzles injecting water into the gas stream. The two subsequent elements keep the parameters of the gas at the inlet to exhauster 17 at the level which corresponds to the working point of the latter.

The heater 15 is needed for the case in which combustion is curtailed in the engine chambers when the gas temperature at the inlet to the exhauster drops somewhat too low. To prevent the ignition of the unburned fuel in the heater, the latter is of tubular construction and provided with hot-water heating. The gas temperature behind the exhauster again rises by approximately 200°C and the gases are therefore again cooled in heat exchanger 18 and the spray-nozzle injector cooling device 19 before entering the second exhauster 20.

The rated regime of the exhauster must be maintained by the appropriate control of the air pressure and temperature at the inlet and the air flow rate. Otherwise, the exhauster may enter a surge regime or overspeed [enter a regime of intolerable numbers of revolutions]. The weight flow rate of air in exhauster 20 is greater than in exhauster 17, because of the removal of the air from the surrounding medium into the spray-nozzle injection cooling device 19. The pressure at the inlet to the exhausters is kept constant by means of the bypass valves. The exhausters are operated by electric-motor multipliers.

If it becomes necessary to supply a large quantity of air, a pressure regulator automatically closes valve c and opens valve f in the engine being tested, thus preventing a change in the operating regime of the exhausters. However, with a reduction in the air flow rate the bypass valve c opens, while bypass valve g of the exhauster acts as a safety valve. The required "altitude" is achieved by controlling the air flow rate with valve c and by controlling the pressure by means of valve f. The required air temperature is achieved by means of bypass valve b of the second expansion turbine.

High-altitude tests of turboprop engines with propellers present particular difficulties. Figure 89 shows the diagram of a stand on which it is possible to test a TVD [turboprop engine] both on the

ground as well as under high-altitude conditions. In the latter case
the air at the inlet to the engine is supplied from the compressor sta-
tion through tubes 2. The air by means of which the propellers are
loaded is taken from the atmosphere through the noise-reduction device
1 and is applied against the propellers by means of an adjustable fit-
ting 5. The diameter of the latter may change within a wide range from
2.5 to 6.0 m. This measure of control should eliminate pulsations at
the tips of the propeller blades. The fitting may be shifted forward
or back, depending on the length of the TVD [turboprop engine]. The
exhaust gases from the engine are cooled in cooling devices and re-
moved by the exhausters. The streams from the propeller pass through
the noise mufflers 3.

Figure 90 shows a diagram indicating the positions of the basic
structures and devices of the high-altitude testing laboratory, de-
signed for tests of turbojet and turboprop engines. Conditions corres-
ponding to high velocities and flight altitudes (approximately $M = 2.5$
and $H = 21,000$ m) can be simulated at the laboratory. For purposes of
controlling the above-indicated parameters within the required range,
the air pressure at the inlet to the engine must be kept between 0.07
and 3.8 kg/cm^2 and the temperature of the air must be kept within a
range from -90 to $+190^\circ$C, while the pressure of the air surrounding
the engine must be kept between atmospheric pressure and 0.035 kg/cm^2,
which corresponds to the maximum given altitude.

The high-altitude installations of the laboratory require much
power; for example, the electric motors employed to drive all of the
compressors may exhibit power of the order of 30,000 kw.

The laboratory has an inlet division in which the air is brought
to the proper parameters, and there is also an outlet section. These
two sections are found in individual buildings.
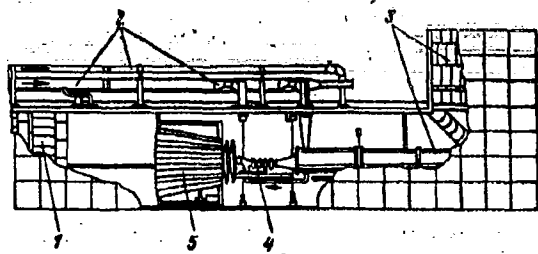
Fig. 89. Diagram of TVD [turboprop en-
gine] test stand. 1) Device for muffling
the sound of the inlet air; 2) supply of
air from compressor; 3) mufflers for ex-
haust and exhaust pipe; 4) TVD [turbo-
prop engine] installed for purposes of
high-altitude tests; 5) adjustable air
fitting.
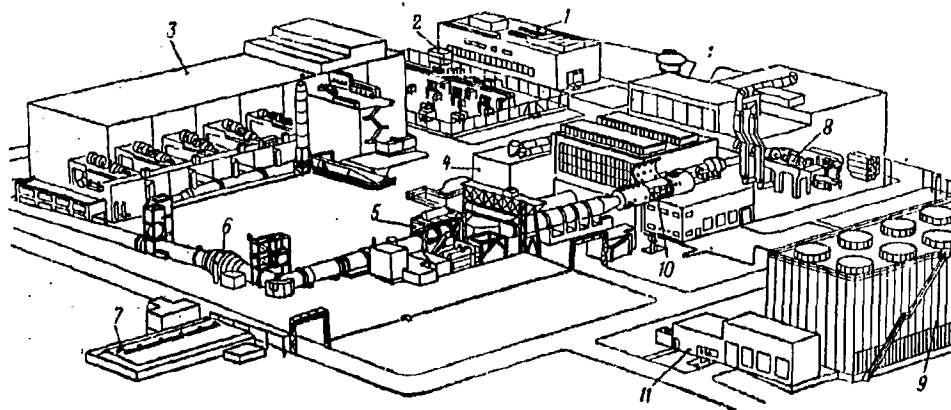
Fig. 90. Diagram showing positions of basic structures and devices
at the high-altitude laboratory. 1) Administrative compound; 2)
substation; 3) exhauster housing (outlet section); 4) building
housing compressor test-stands; 5) primary cooler; 6) secondary
cooler; 7) fuel storage; 8) compressor station (inlet section); 9)
cooling tower; 10) pressure chamber; 11) pump station.

The compartment used for testing under conditions of high alti-
tudes consist of two chambers. The first of these chambers is an air
intake which receives the air at the required temperature and pressure.
The air intake is equipped with special inlet guide-vane diaphragms
and blades to straighten the flow; in addition, there is equipment to
measure temperature and pressure. The second chamber contains the en-

gine which is mounted on [special] units equipped with sensing elements for the measurement of thrust by means of special balances. The test section is fitted out with explosion-proof valves.

The testing of a PVRD [ramjet] and its elements in installations making it possible to simulate flight speeds of M = 2-3 is associated with a tremendous consumption of power. In this connection it is frequently necessary to resort to supersonic intermittent wind tunnels. There are three types of supersonic short-duration installations that are possible and are used, and these differ from one another in the manner in which the supersonic flow is achieved.
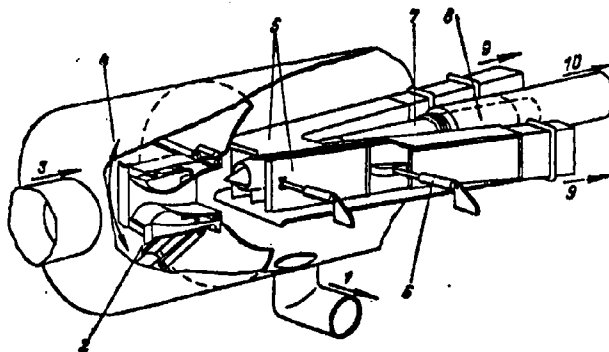
Fig. 91. Diagram of test section of a supersonic installation. 1) Connection tube to exhauster; 2) adjustable supersonic nozzle; 3) inlet for air of given parameter; 4) turn angle to simulate flow drift; 5) diverging variable-geometry channels for blower air; 6) pistons to shift channel walls; 7) engine; 8) water-cooled exhaust tube; 9) to subsonic diffuser and blower-air cooler; 10) to engine exhaust-gas cooling device.

In the first type the tanks [reservoirs] are filled with air compressed to several hundreds of atmospheres, this air being released in the form of a supersonic stream against the object being tested (an engine, an aircraft model, a missile, etc.).

In the second type a vacuum is created in the receiver. Air from

- 153 -
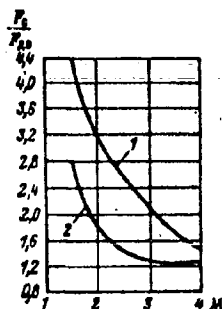
Fig. 92. Dimensions of streamlined nozzles required to simulate flow conditions at inlet to PVRD [ramjet]. 1) Maximum nozzle dimensions for great angles of attack and subcritical regimes; 2) minimum nozzle dimensions at small angles of attack and supercritical regimes.

the surrounding medium flows into the receiver and an engine or some other object is tested in the airstream.

The third type of installation represents a combination of the first two.

Installations of the types considered above require no powerful compressors, but it is difficult to carry out experiments in these installations because of the short time interval during which the stream parameters can be kept constant.

In the testing of PVRD [ramjets] it is extremely important to clarify the influence exerted by the angles of attack on engine operation. To simulate changes in the angles of attack it is the general practice in these installations to change not the slope of the engine's axis but that of the blower-nozzle axis. A drawback of such an installation lies in the fact that it is necessary to change the blower nozzle when attempting to determine the engine characteristics with respect to the M(ach) number.

Figure 91 shows a diagram of the test section of a supersonic high-altitude chamber with a variable nozzle. The supersonic rectangular nozzle is controlled by means of two flexible walls which can be shifted between fixed walls. The diffuser for the air flushing the engine is also equipped with adjustable side walls. The simulation of flow drift at the inlet is achieved by turning the entire nozzle. The pressure in the chamber compartment in which the engine and the diffuser are housed is maintained to coincide with the given flight "alti-

tude."

Primary control is achieved by changing the critical section of the nozzle. The bleeding of air and the control of the diffuser cross section is handled automatically and corresponds to the high-altitude pressure in the chamber. The control system must prevent the occurrence of surge through the system.

In designing systems for the supply of air to installations with free flow, the ratio of the blower-nozzle area F_s to the area F_{dv} of the inlet portion of the engine is of particular interest. A graph of the recommended F_s/F_{dv} ratios for axisymmetrical nozzles for various M(ach) numbers is given in Fig. 92.

3. INSTALLATIONS FOR THE TESTING OF BLADED EQUIPMENT

The studies and adjustment of compressors and turbines plays a great role in VRD [ramjet] design projects. Multistage axial compressors and turbines whose basic element is a blade ring are widely used
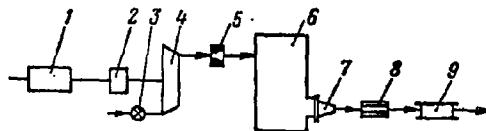
Fig. 93. Schematic diagram of installation for recording of blade-ring characteristics. 1) Electric motor; 2) multiplier; 3) throttle; 4) compressor; 5) metering nozzle; 6) receiver; 7) nozzle; 8) guide vanes; 9) test section of installation with blade ring.

in contemporary air-reaction engines. The proper selection of the blade ring provides for improved characteristics of the bladed machine and raises its efficiency. It is natural therefore that particular attention is being devoted to studies of blade rings.

A schematic diagram of an installation for the determination of blade-ring characteristics is given in Fig. 93. Air passes from the

compressor through the receiver, nozzle, and inlet guide-vane assembly into the test section of the installation in which the angle of attack, the blade-setting angle, and the spacing between the blades [buckets] can be changed within a wide range.
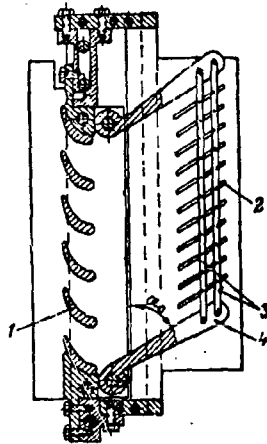
Fig. 94. Structural diagram of test section of installation for determination of blade [profile] characteristics. 1) Blade ring under investigation; 2) guide plates; 3) connecting rods; 4) rotating shaped inserts.

Fig. 95. Diagram of installation for determination of blade-ring reaction force. 1) Diffuser; 2) blade ring; 3) receiver; 4) flexible element; 5) support; 6) metering nozzle.

Figure 94 shows one of the versions of the structural diagram of the installation test section. The angle of attack can be changed by means of two rotating shaped inserts 4. The inserts form a passage in which a ring of guide plates 2 can be mounted to provide for the better straightening of the stream. The given magnitude of α_0 is monitored by means of a dial.

The pressure and velocity fields before and after the blade ring 1 being tested are recorded by means of pneumatic probing. It should be pointed out that this method is extremely cumbersome and requires the expenditure of considerable time to carry out the experiment; however, if these experiments are carried out carefully, the method ensures high measurement accuracy.

- 156 -

The reaction-force balancing method considered below makes it possible to derive the integral characteristics of blade rings at a considerably reduced expenditure of time for the experiments. The high productivity of the method makes it possible easily to obtain a comparative evaluation of the blade rings, differing in blade shape, and in geometric and regime parameters.

Figure 95 shows the diagram of an installation for the balancing of reaction force, this installation also making it possible to determine the circumferential and axial components of this force. The air from the compressor passes through the metering nozzle 6 and diffuser 1 from which it is directed into receiver 3 in which the blade ring 2 is mounted. The receiver with the blade ring is mounted in the vertical section of the air duct which is equipped with a fixed support 5 at the top.

The blade ring being tested is mounted on a horizontal flat surface. The reaction force is absorbed by a flexible element 4 which is simply a thin-walled section of the duct. Four strain gauges are attached to the surface of this element along two mutually perpendicular axes ab and cd (the section AA). The presence of two sensing elements on a single axis increases the sensitivity of the bridge and enhances thermal compensation. The two sensing elements that are situated on a single axis form the two arms of the measuring bridge, while the remaining two arms are connected to a special rheochord [slide wire] which makes it possible to calibrate the bridge.

The sensing element situated on the ab axis measures the axial component R_a of the reaction force R, while the sensing element situated on the cd axis measures the circumferential component R_u of the reaction force.

Knowing the true air flow rate G_v, measured by means of the meter-

ing nozzle, and knowing the reaction force R

$$R = \sqrt{R_a^2 + R_u^2}, \tag{108}$$

whose components R_a and R_u have been determined by means of strain-gauge balances, makes it possible to determine the mean velocity at the outlet

$$c_1 = \frac{gR}{G_a}, \tag{109}$$

the velocity and flow-rate coefficients

$$\varphi = \frac{c_1}{c_{1T}} \tag{110}$$

and

$$\mu = \frac{G_a}{G_{a.T}}, \tag{111}$$

as well as the mean stream angle at the outlet

$$\alpha_1 = \arctan \frac{R_a}{R_u}. \tag{112}$$

The value of the velocity c_{1t} and that of the flow rate $G_{v.t}$ are found from the usual gasdynamic formulas.

The installation under consideration makes it possible to determine the influence exerted solely by the M(ach) number on the characteristics of the blade rings.

Figure 96 shows a diagram of an installation for airstream tests of blade rings, this installation permitting consideration of the influence exerted by the Re(ynolds) numbers on the characteristics. It is possible in this case to change the M and Re numbers independently of one another, and this is achieved by changing the differences in pressure and density of the air flowing past the blade ring in this system that is closed airtight during the test. Such test results are used in calculating the high-altitude characteristics of engines.

The air proceeding from compressor 3 is cooled in heat exchanger 4 and is passed through nozzle 6 to the blade ring 7 being tested. The

- 158 -
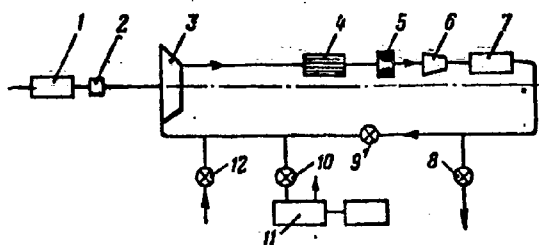
Fig. 96. Schematic diagram of installation for airstream tests of blade rings. 1) Electric motor; 2) multiplier; 3) compressor; 4) heat exchanger; 5) metering nozzle; 6) nozzle; 7) blade ring under study; 8) exit valve; 9) throttle; 10) vacuum-pump valve; 11) vacuum pump; 12) inlet valve.
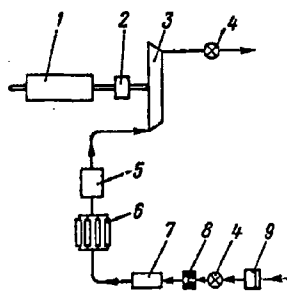
Fig. 97. Diagram of installation for testing compressor stage. 1) Electric motor; 2) multiplier; 3) compressor stage; 4) throttle valve; 5) cooler; 6) air dryer; 7) heat exchanger; 8) metering diaphragm; 9) air filter.
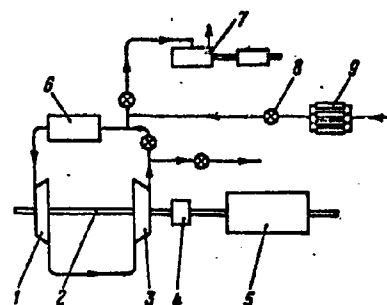
Fig. 98. Diagram of closed-type vacuum installation. 1) Air turbine; 2) spring; 3) compressor; 4) multiplier; 5) electric motor; 6) heat exchanger; 7) vacuum pump with electric motor; 8) throttle valve; 9) air dryer.

air flow rate is determined by means of metering nozzle 5. A large number of valves are provided for in the installation, these being necessary for purposes of control. The density of the air in the closed system of the installation is reduced by means of vacuum pump 11.

Let us now turn to the examination of installations for the deter-

- 159 -

mination of compressor and compressor-stage characteristics.

Figure 97 shows the diagram of an installation for the testing of the stages of an axial compressor. Regimes with various air flow-rate and parameter values at the inlet can be established for the compressor stage being tested by introducing appropriate changes in the revolutions of the electric motor, the positions of the throttle valves, and the thermal effect on the air in the heat exchanger and the cooler. The diagram of the installation for the testing of a full-scale compressor is analogous to the one described. A compressor is frequently studied directly within the engine system. However, in this case the compressor characteristic may not be recorded completely, but only within a comparatively narrow range.

Figure 98 shows the diagram of a closed-type vacuum installation by means of which it is possible to conduct tests at the same volumetric air flow rate as under actual conditions. The weight flow rate of air in this case will be lower. The compressor being tested, the throttling device, the heat exchanger, and the air turbine which returns a portion of the power expended on driving the compressor are included in this system. A powerful electric motor (as indicated in the diagram) or a gas turbine may be employed as the powerplant in this case.

The air filling the installation is first dried in order to avoid the icing of the measuring instruments during the low-temperature regimes. The test regime is controlled by changing the revolutions, the quantity of removed heat, the pressure at the inlet to the compressor, and also by means of throttling. The temperature of the air at the inlet to the compressor can be changed over a wide range, and this is extremely important for purposes of simulating high-altitude and high-speed conditions during the tests.

- 160 -

It is not necessary to use an air turbine in the installation, since the throttle and the heat exchanger make it possible to establish the required parameters. However, in this case considerable losses during the throttling of the air take place, and the heat exchangers prove to be extremely cumbersome.

The turbine characteristics are recorded on special installations.

The power of the turbine is absorbed by means of a hydraulic brake or compressor (Fig. 99) which draws air in from the atmosphere. The power required by the air brake 3 is controlled by changing the air flow rate by means of valve 1. As can be seen from the diagram, gases from chamber 13 enter the turbine 4 being tested. The turbine power, equal to the compressor power, is determined by the following formula:

$$N_\tau \approx N_\kappa = \frac{G_s c_p (T_2^* - T_1^*)}{75A}.$$ (113)

where T_1^* is the stagnation temperature of the incoming air; T_2^* is the stagnation temperature of the air at the outlet from the air brake 3; G_v is the air flow rate through the air brake; c_p is the specific heat of the air.

In the installation under consideration the turbine and the air brake are controlled independently, this making it possible to change the operating regime of the turbine within a wide range. The testing of turbines whose power is absorbed by means of a hydraulic brake produces more accurate results.

4. INSTALLATION FOR THE TESTING OF COMBUSTION CHAMBERS

In view of the fact that the problems associated with a wind-tunnel chamber and combustion processes within such a chamber are extremely complex, existing combustion chambers are perfected, primarily, by experimentation.

- 161 -
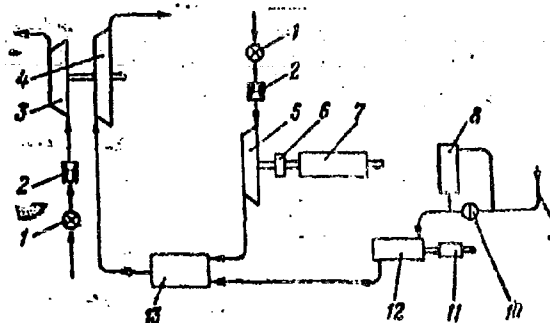
Fig. 99. Diagram of installation for turbine testing. 1) Throttle valve; 2) metering diaphragm; 3) air brake; 4) turbine being tested; 5) compressor; 6) multiplier; 7, 11) electric motors; 8) sampler; 9) fuel manifold; 10) valve; 12) fuel pump; 13) combustion chamber.
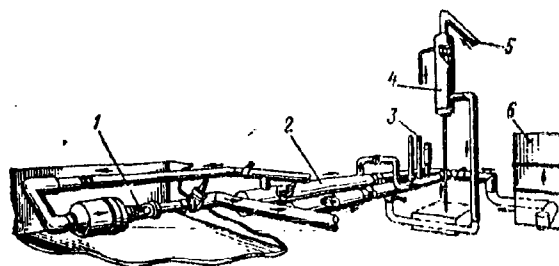
Fig. 100. Diagram of installation for study of combustion processes. 1) Combustion chamber being tested; 2) heat exchanger; 3) air feed; 4) water cooler to cool gases; 5) high-altitude exhaust system; 6) muffler for exhaust to atmosphere (ground conditions).

In order to reduce expenditures on the design of new chambers, it would be desirable to switch from natural [full-scale] tests to tests of models, the final test being conducted on full-scale chambers. However, because of the difficulties encountered in modeling the chambers, this "two-stage" design method is not used.

Figure 100 shows the diagram of a laboratory installation for the testing of combustion processes. As can be seen from the diagram the

air enters chamber 1 from the compressor station through heat exchanger 2 in which it is heated by the gases removed from the chamber. The presence of heat exchangers makes it possible to have an elevated temperature at the inlet to the combustion chamber — this temperature characteristic of combustion-chamber operating regimes in the case of high-velocity flights. Moreover, the special suction system with the cooler 4 makes it possible to achieve low pressures at the inlet, these corresponding to high-altitude conditions.

In carrying out experimental tests of combustion chambers, it is necessary to devote particular attention to the determination of the heat-liberation coefficient ξ, the pressure-recovery factor σ^*, as well as to determine the uniformity of the temperature field at the outlet from the chamber.

The heat-liberation coefficient is defined as the ratio of the quantity of heat Q_d actually liberated during the combustion to the quantity of heat Q_t supplied with the fuel:

$$\xi = \frac{Q_{\scriptscriptstyle K}}{Q_{\scriptscriptstyle T}}. \qquad (114)$$

The quantity Q_t can always be determined by calculation if the fuel flow rate and its heating value are known. The determination of Q_d presents considerable difficulty.

In principle, Q_d can be determined by the calorimetric method, by changing the temperature and composition of the gases directly, as well as by weight methods based on the measurement of the reaction momentum of the gas streams leaving the chamber. The above-enumerated methods of determining ξ automatically include losses through the chamber walls to the ambient medium.

The calorimetric method is extremely cumbersome, since it requires the development of a large calorimeter for the determination of the

quantity of heat released by the exhaust gases from the chamber that are cooled in the calorimeter.

It is necessary to point out that the flow at the outlet from the combustion chamber is not uniform with respect to temperature, density, and velocity, as well as with respect to gas composition. In this connection a gas sample is taken from several points of the section, and the mean-mass value of ξ is determined from the following expression:

$$\xi = \frac{\sum_1^n G_{r\,i} c_{pi} \Delta t_i}{Q_T},$$

$$(115)$$

where $G_{g\,i}$ is the gas flow rate through the corresponding section; c_{pi} is the mean specific heat of the gases in this section; $\Delta t_i = T^*_{3i} - T^*_2$ is the heating of the gases in the section 2-31.

The weight method offers considerably less difficulty, i.e., the method of measuring the reaction force of the gas stream emanating from the chamber. This method immediately yields the mean-mass value of ξ without tedious measurements at separate points along the flow.

In order to determine the pressure-recovery factor for the combustion chamber

$$\sigma^* = \frac{p^*_3}{p^*_2}$$

$$(116)$$

it is necessary to know the total pressure p^*_2 at the inlet to the chamber and the total pressure p^*_3 at the outlet from the chamber. The total pressures do not remain constant through these sections. For this reason it is necessary to use the following formula

$$\sigma^* = \frac{\sum_1^a G_{i\,i} p^*_{3i}}{\sum_1^a G_{v\,i} p^*_{2i}} \frac{G_u}{G_t},$$

$$(117)$$

which gives the mean-mass value of σ^*. In this formula $G_{g\,i}$ and $G_{v\,i}$ represent, respectively, the gas and air flow rates through the ith
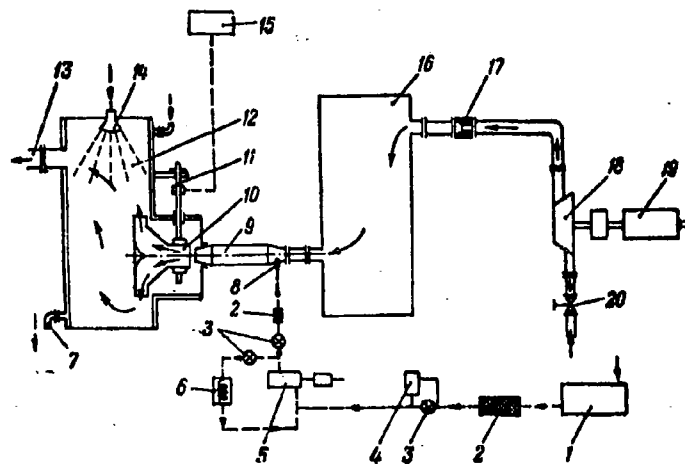
Fig. 101. Schematic diagram of installation for testing model combustion chambers under ground conditions. 1) Fuel tank; 2) filters; 3) stopcocks; 4) sampler; 5) fuel pump; 6) cooler; 7) drain for removal of water from water jacket of exhaust receiver; 8) spray-nozzle injector; 9) chamber being studied; 10) trap to balance exhaust gas stream; 11) trap rod to which strain gauges are attached; 12) exhaust receiver; 13) outlet of gases to atmosphere; 14) water spray; 15) oscillograph; 16) receiver; 17) metering diaphragm; 18) compressor; 19) compressor drive; 20) throttle valve.

sections; p^*_{31} and p^*_{21} represent, respectively, the total pressures in the sections 31 and 21; G_v and G_g represent, respectively, the air and gas flow rates through the chamber.

The total head at the various points of the section under investigation is measured by means of a total-head fitting equipped with "rakes" or "combs." The sensing elements on such a total-head "rake" are positioned so that they are located in the middle of the equal-sized areas into which the given section has been divided. This distribution of the sensing elements makes it possible to determine the mean pressure value. The high gas temperatures at the outlet from the chamber make necessary the utilization of sensing elements that are cooled or made of heat-resistant materials.

- 165 -

Figure 101 shows a schematic diagram of an installation for the testing of model combustion chambers under ground conditions. A special device for the measurement of the reaction force of the gas stream emanating from the chamber is used in this installation.

Trap 1 (Fig. 102), suspended in cantilever fashion from rod 2, is rigidly attached in fixed sleeve 3 and it shifts under the action of the flow entering the trap from the chamber. The rod is subjected to bending deformations; two identical wire resistance sensing elements (strain gauges), representing the two arms of the Wheatstone bridge, are attached to the parallel surfaces A and B of the rod, these surfaces equidistant from the trap shaft.

These two sensing elements, experiencing identical temperature conditions, but subjected to various deformations (tension and compression), provide for thermal compensation, i.e., they eliminate the influence of the change in the temperature of the surrounding medium and the rod on the instrument readings, and they raise the sensitivity of the bridge by a factor of two. The most convenient circuit for the measurement of deformations is the circuit for an unbalanced bridge operating on alternating current. The changes in the current in the bridge, resulting from the deformation of the rod, are proportional to the magnitude of the shift of the trap along the xx-axis, i.e., they are proportional to the value of thrust and are recorded by means of an oscillograph.

Figure 103 shows a diagram of a device with an induction sensing element that serves also to balance the exhaust stream. The coupling rod 5 of the sensing element is attached to diaphragms 3 and 4. Under the action of the pressure of the products of combustion the sensing element shifts and changes the clearance δ between armature 6 sitting on the coupling rod and the magnetic circuit 7 of the transformer in-
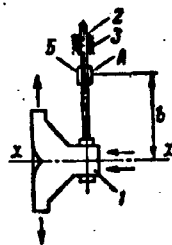
Fig. 102. Diagram of impulse meter with wire sensing elements. 1) Trap; 2) flexible rod; 3) sleeve.
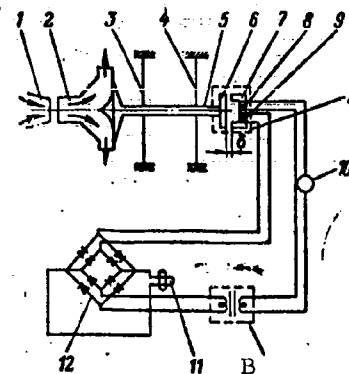
Fig. 103. Diagram of impulse meter with induction sensing element. 1) Nozzle; 2) trap; 3, 4) diaphragms; 5) coupling rod; 6) armature; 7) core; 8) primary winding; 9) secondary winding; 10) sound generator; 11) loop oscillograph; 12) detector. A) Sensing-element unit; B) compensator unit.

duction coil. The instrument is connected to an AC supply. This instrument exhibits the advantage of eliminating the need to amplify the pulse, even if the values of the latter are low.

5. INSTALLATIONS FOR THE TESTING OF AUXILIARY ELEMENTS OF AVIATION ENGINES

The auxiliary engine units are generally tested in laboratories. The turbine starters, generators, fuel and oil pumps, various regulators and distributors, auxiliary gas turbines, spray-nozzle injectors, devices to drive the aircraft units, etc., are initially tested on special installations.

A powerful starter is required to actuate a gas-turbine engine that develops great thrust. In this case a turbine starter whose operation is limited in terms of shutdown time and number of revolutions is frequently employed. An analysis of the specifics of turbine-starter operation indicates that the method of static tests for conventional

- 167 -
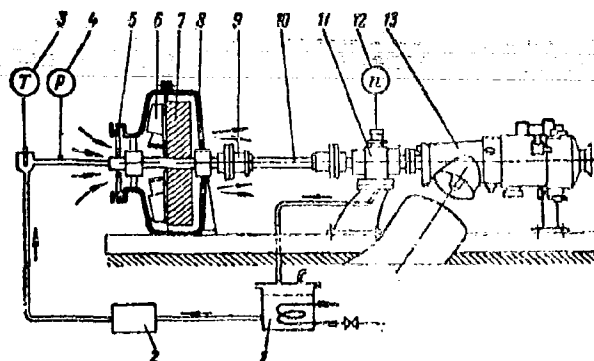
Fig. 104. Diagram of test-stand for dynamic
tests of turbine starters. 1) Oil tank with
heater; 2) pump; 3) thermometer; 4) manom-
eter; 5) rotating valve; 6) air-brake vanes;
7) flywheel; 8) air-brake housing; 9) clutch
coupling; 10) torsion shaft; 11) oil valve;
12) tachometer; 13) turbine starter.

gas-turbine engines involving the measurement of engine parameters in

constant stabilized regimes does not provide for sufficiently accurate

control of the operation of the starter unit prior to its installation

in the main engine. The approximation of the parameters of the starter

GTD [gas-turbine engine] to the operational parameters under test-stand

conditions is possible only through a combination of the corresponding

starter load and a regime of continuous acceleration.

Figure 104 shows a diagram of a stand for dynamic turbine-starter

tests making it possible to observe a regime close to the operational

acceleration regime through an entire starting cycle and to measure

the instantaneous power values for various [numbers of] revolutions of

the drive shaft. The stand is equipped with a dual supported rotor of

simple design and a drive spring – the elastic portion of the torsion

dynamometer. Similar to the transmission of the main engine, the test-

stand rotor during the starting procedure develops inertial resistance

to rotational acceleration and blower deceleration.

The rotor is a steel disk-flywheel seated on the shaft, the end

surface of the disk being fitted out with aerodynamic-deceleration
blades, similar to the blades of a centrifugal blower. There are open-
ings in the rotor frame for the inlet and outlet of air. The inlet
openings can be throttled by means of a special rotating screen.
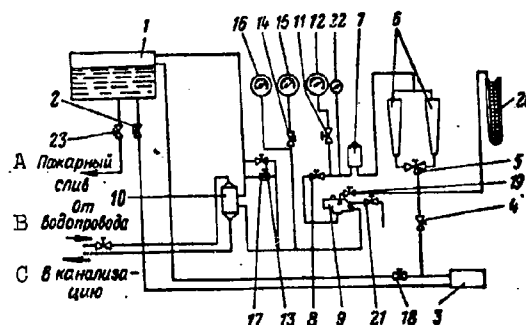
Fig. 105. Diagram of hydraulic installa-
tion for testing of fuel pumps. 1) Flow
tank; 2) stopcock; 3) pump; 4) low-pres-
sure throttle valve; 5) distributor
valve; 6) rotameters; 7) low-pressure
filter; 8) pump inlet valve; 9) pump be-
ing tested; 10) radiator; 11) manometer
stopcock for pressures below 6 kg/cm^2;
12) manometer for pressures below 6
kg/cm^2; 13) high-pressure throttle valve;
14) manometer valve for pressures below
25 kg/cm^2; 15) manometer for pressures
below 25 kg/cm^2; 16) manometer for pres-
sures below 150 kg/cm^2; 17) safety valve;
18) low-pressure safety valve; 19) valve;
20) piezometer; 21) valve; 22) distance-
reading thermometer; 23) emergency valve.
A) Emergency drain; B) from water main;
C) to water main.

The power for the turbine starter in the case of the acceleration
regime is partially accumulated in the flywheel and partially absorbed
by the air brake. A hydraulic torsion dynamometer is used as the de-
vice to measure M_{kr} on the starter shaft.

Great attention is being devoted in the laboratories to the test-
ing of fuel-system units. As an example, Fig. 105 shows a diagram of

a hydraulic system for an installation used to test fuel pumps. During the testing of these pumps the following characteristics are checked: the capacity of the pumps, the control and operating range of the overspeed governor, the functioning of the valves, the over-all airtight sealing, etc.

When the test stand is in operation the fuel is passed from the flow tank 1 through the stopcock 2 under the action of gravity into pump 3. Under the pressure generated by the pump the fuel is then passed through the low-pressure throttle valve 4 to one of the rotameters 6 and then through low-pressure filter 7 and valve 8 into the pump 9 being tested. From this pump the fuel passes through radiator 10 and partially through the high-pressure throttle valve 13, from which it returns to flow tank 1.

The fuel pressure in front of the rotameters is controlled by means of the low-pressure throttle valve 4. The fuel pressure in front of valve 8 is monitored by means of manometer 12. The pressure at the inlet to the pump is controlled by valve 8 and monitored by means of piezometer 20. The pressure at the outlet from the pump is controlled by the high-pressure throttle valve 13 and monitored by means of manometers 15 or 16, depending on the magnitude of the pressure. The temperature of the fuel at the inlet to the pump being tested is monitored by means of a distance-reading thermometer 22 and controlled by means of the water flow rate through radiator 10.

[List of Transliterated Symbols]

157	в = v = vozdukh = air
158	в.т = v.t = vesy tenzometra = strain-gauge balances
158	т = t = tenzometer = strain gauge
161	т = t = turbina = turbine
161	к = k = kompressor = compressor
163	д = d = deystvitel'no = actual
163	т = t = toplivo = fuel
164	г = g = gaz = gas

Chapter 5

TESTING STATIONS

1. CLASSIFICATION OF TESTING STATIONS AND REQUIREMENTS IMPOSED ON SAME

Testing stations are employed for purposes of testing aviation engines under ground conditions. The stations represent a complex of built-up structures equipped in the proper fashion. The basic structures in this case include the following: rooms (testing cabins) in which the engines to be tested are installed; control rooms from which the engines are controlled and the functioning of the engines is monitored; and finally there are production buildings to house the various power-supply systems for the testing installations.

The auxiliary structures required to service all of the stations include a transfer station, machine and electrical workshops, a monitoring-measuring instrument division, production departments, administrative sections, a central fuel storage, etc.

The central fuel storage is situated approximately 200 m from the station building and it consists of a certain number of underground reservoirs that are interconnected. The fuel is supplied mechanically to the testing installations (by means of pumps), or under the pressure of dry air or some inert gas forced into the reservoirs.

Each testing station is fitted out with a special piece of equipment by means of which it is possible to determine the magnitude of thrust or torque, or both, in the testing of a TVD [turboprop engine]; in addition, each testing installation has the following systems: fuel, oil, starting, air (compressorless VRD [air-reaction engines]), etc.

- 172 -

There is an engine control panel on the installation, and this panel is equipped with monitoring-measuring instruments. The above-enumerated equipment and systems make it possible to carry out the tests and to record the required engine characteristics.

In order to ensure safety and hygienic conditions, the station structures have been provided with ventilation systems, they have been soundproofed, fire-fighting equipment has been installed, etc.

Various types of stations are employed in testing practice. Depending on the purpose of the test, stations can be divided into experimental and routine stations. The type of engine being tested determines the use of a station for the testing of compressorless air-reaction engines or of a station for the testing of air-reaction engines with compressors, while the operating conditions determine the use of an open- or closed-type of station.

In selecting the type of station, we find that the determining factors are the following: the type of engine; the purpose of the test, the designation of the enterprise of which the station is a part; the type of equipment used in the station; the nature of the terrain in which the station is situated, and the climatic conditions prevailing over this terrain; and finally, the cost of the test station.

The open-type stations are the simplest; in stations of this type the engines being tested are kept in the open air and they are protected against atmospheric precipitation only by means of hangar-type structures, the control and observation operations being conducted from rooms situated alongside. Stations of this type are quite mobile and can easily be transferred from one area to another.

Cases are possible in which it would be expedient to reject the use of an engine-mounting installation, but rather to mount the engine directly in the aircraft, conducting the test in this manner. Such an

- 173 -

installation would make it possible to measure the actual force of engine thrust, while at the same time taking into consideration the losses in the intake and exhaust channels of the aircraft for all operating regimes of a TRD [turbojet engine].

Open-type stations are comparatively inexpensive, but exhibit the following significant drawbacks: they cannot be set up near populated areas because of a lack of special noise-reducing systems; the setting up of an engine in the open air results in inconvenience for the personnel servicing the station; it hinders the conditions under which the tests are carried out, etc. Open-type testing stations are used at repair bases.

Testing stations exclusively of the closed type, in which the engine is kept within an enclosure throughout the entire period of the test, are used in series-production aviation-engine building plants situated in the vicinity of major populated centers. Closed-type stations provide for the required convenience of personnel and make it possible to use highly effective noise-reduction methods.

Several versions of closed-type testing stations whose specific characteristics are governed by the tasks and requirements enumerated below have gained widespread acceptance, depending on the design of the test sections and their location relative to the control rooms.

In series production a testing station must provide for testing with minimum expenditure of time on the fitting out and mounting of the engine, for testing conditions that simulate the operational conditions of the engine to the maximum, for the supply of great quantities of filtered fuel, for testing economy, for fire safety, and for noise-reduction and proper ventilation.

This chapter presents the fundamental data on closed-type factory stations for the testing of turboprop and turbojet engines.

2. TEST SECTIONS

The following requirements are imposed on test sections:

1) the inlet portion of the test section must provide for the supply of air to the engine being tested, this air to be free of dust and exhaust gases;
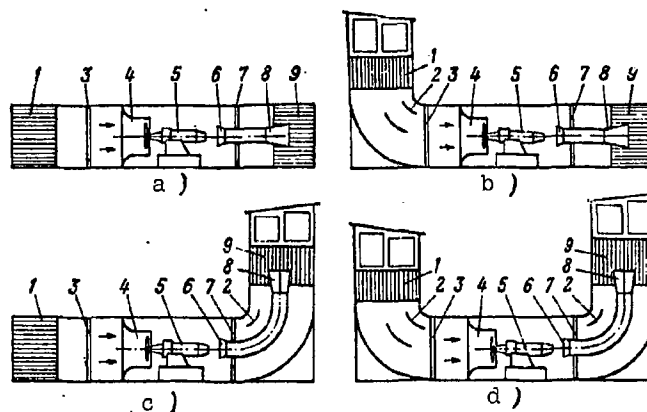
Fig. 106. Types of test sections. 1) Entry with noise absorber; 2) guide vanes; 3) inlet gates; 4) aerodynamic wind-tunnel ring (for testing of TVD [turboprop engine]); 5) engine; 6) ejector; 7) outlet gates; 8) outlet diffuser; 9) outlet with noise absorber.

2) the inlet portion must be fitted out with a noise absorber;

3) the test section must provide for a supply of air from the inlet portion to the working section which carries the engine being tested;

4) the exhaust portion of the test section must be equipped with a device to remove the exhaust gases and with a sound-absorption device to reduce the noise produced by the exhaust stream;

5) the test section must be provided with doors in order to permit entry to and exit from the test section for the engines and the lifting devices;

6) the walls of the test section must be strong and protect the

servicing personnel in the case of an accident or if the engine should be destroyed during the course of a test.

Since test sections are designed to serve for the testing of any type of gas-turbine engine, the parameter which determines the dimensions of the installation is the air flow rate through the engine and the propellers, i.e., a test section is designed to be able to withstand the power developed by some future TVD [turboprop engine] during the course of a test.

Four types of test sections, like the ones shown in Fig. 106, are used in testing practice. Of these, the most common are the test sections shown in Fig. 106a and b. The installation of a vertical shaft at the inlet provides for a supply of pure air to the engine. The horizontal ejection of the products of combustion makes it possible to reduce the noise adequately at a lower cost than would be possible in the case of vertical ejection. From this standpoint, a test section with two horizontal shafts exhibits the best conditions for noise absorption and it also exhibits the best aerodynamic characteristics.

The selection of a given type of test section is governed by the location of the factory, the type and power of the engine being tested, and by the distance between the test station and other plant structures.

The test section, as can be seen from Fig. 106, consists of three main parts: the inlet section, the test section, and the exhaust section. A stand is positioned on a special foundation in the test section, the engine to be tested being mounted on this stand. If the engine is of the turboprop variety, it is necessary to install an aerodynamic wind-tunnel ring at the inlet to the test section in such a manner that the propeller of the engine is situated inside this ring and that their axes coincide. The distance between the propeller blade

tips and the walls of the ring must not be less than 0.5-0.75 m, thus providing adequate clearance to avoid the vibrations that are excited by the movement of the blade tips. The aerodynamic wind-tunnel ring ensures better conditions of airflow past the propeller.

At the outlet from the test section we find an ejector tube through which the products of combustion are removed, thus reducing the temperature and velocity of the exhaust gases (due to the intake [suction] of air). The ejector tube and the engine must be situated on a common axis.

Figure 107 shows the working section of a test installation. The engine is passed into the test section through special gates, and then an electrically operated lift moves the engine to the test stand that is mounted on the special vibration-absorbing foundation.

The vibrations in the foundation are partially absorbed by an insulation cushion 2 made up of cork plates, specially treated wood, or felt. There is an air space 15-20 cm thick to provide insulation against lateral vibrations. The stand foundation must be deeper than the foundation of the building walls in order to reduce the vibrations of the latter.

In order to reduce the fatigue stresses caused by vibrations in the working section, the latter should be constructed of prestressed reinforced concrete, the walls of the structure being approximately 200 mm thick.

Figure 108 shows the engine equipment on the stand in the test section prior to the start of the test, while Fig. 109 shows a TVD [turboprop engine] mounted on the stand.

It is extremely important to make proper selection of the speed of the air in the inlet portion of the test section, as well as to select properly the speeds of the air and the products of combustion in

- 177 -

the exhaust section. Data on the velocity of the air and the exhaust gases in the various segments of a TVD [turboprop engine] test section are presented below to provide the aerodynamic characteristics of test sections.
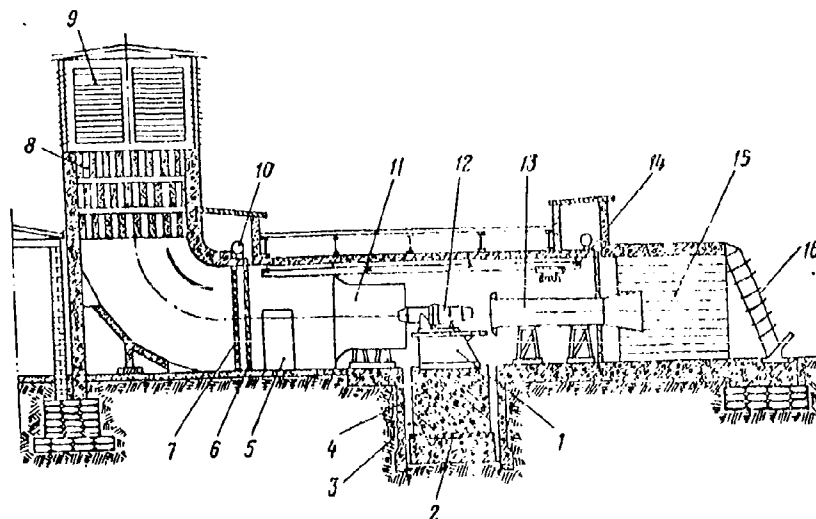
Fig. 107. Test section of testing installation. 1) Stand; 2) insulation cushion; 3) air space; 4) foundation; 5) test-section inlet; 6) louvers; 7) blade ring; 8) inlet noise reducer; 9) air inlet; 10) drive; 11) aerodynamic wind-tunnel ring; 12) engine; 13) ejector; 14) electrically operated lift; 15) outlet noise reducer; 16) repulsion blades.
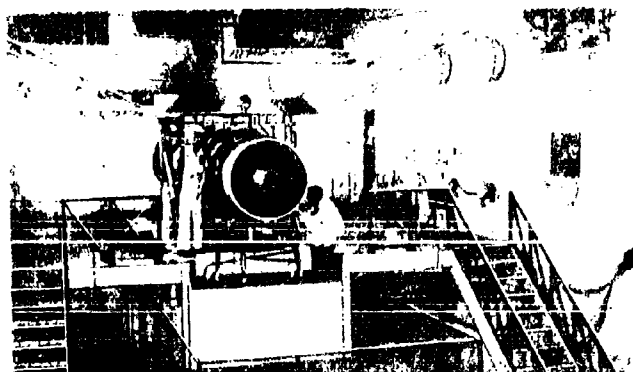
Fig. 108. Readying an engine on the stand prior to the test.
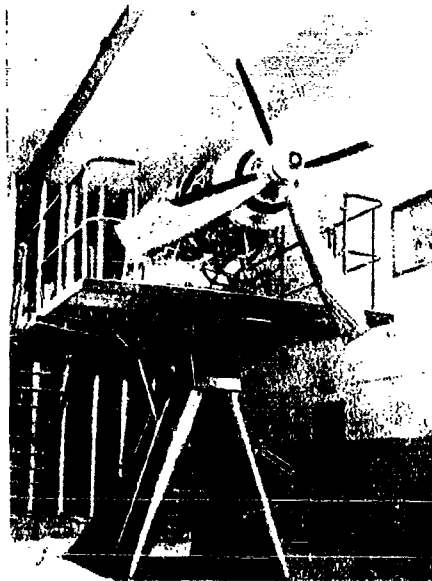
Fig. 109. Turboprop engine on
test stand.

The air is introduced to the suction part at a speed of 10-20
m/sec. The mean speed of the air through the sound-reducing unit may
be assumed to be 20-30 m/sec in the suction section while in the
straightener-grid section the air moves at a speed of 15-20 m/sec. The
speed of the air in the plane cut by the propellers (at the outlet
from the aerodynamic wind-tunnel ring 4 in Fig. 106) is derived from
the calculations for the propeller. When the propeller efficiency is
equal to 0.55 (flight speed $V = 0$), the speed of the air amounts to 45
m/sec.

The velocity of the air is assumed to be of the order of 30-40
m/sec in the noise-reduction units in the exhaust. The speed of the
air at the outlet to the atmosphere is of approximately the same value.
The pressure in the suction part of the test section is generally
lower than atmospheric pressure by a factor of 100-300 mm water col-
umn because of the movement of the air, and it is higher than the at-

mospheric pressure by a factor of 200-400 mm water column in front of the exhaust noise-reduction unit. This circumstance must be accounted for in the strength calculations for the test section.

3. CONTROL ROOMS

During the course of an engine test the technical personnel are located in the control room that is situated next to the test section. To ensure the control of the engine and the monitoring of its operation, the control room must:

1) be sufficiently large to house all equipment, instruments, and personnel;

2) provide facilities for visual observation (through special windows) of the condition of the engine being tested in the test section;

3) guarantee complete safety for the personnel in the control room during the test and it must be properly sound-treated and equipped with good ventilation facilities;

4) be properly lighted (desirably, with natural light during the day).

Depending on the number of test sections serviced, control rooms can be of the individual (one- or two-sided) and joint types. The control rooms servicing more than two test sections are known as joint control rooms. The best conditions for the servicing personnel are provided by an individual control room. The joint control room is more compact, less expensive, and convenient for the management of a shift (the possibility of simultaneously supervising the work of all crews [brigades] servicing an installation).

The selection of a given type of control room is governed by the scheduled engine-production program, the type and power of these engines, the positioning of the engines in the test section, and the design of the test section.

The floor of the control room is installed on special columns and it is not linked with the walls of the test section, thus significantly reducing the vibrations that would be transmitted from the engine being tested.

Special equipment is housed in the control rooms of test stations, and the basic element of this equipment is the engine control panel which is equipped with monitoring instruments.

The control panel is generally installed beyond the plane of engine-rotor rotation. The control units of the engine and its elements and auxiliary systems are mounted on the control panel, as are the monitoring instruments, the auxiliary instruments required for the measurement of the test magnitudes of interest, and finally there is a signaling system that is also part of the control panel. An observation window is situated immediately above the control panel.

The fundamental requirements imposed on a control panel call for the positioning of the instruments and control units in such a manner as to make possible engine control with the greatest convenience as well as to observe the instruments and record their readings.
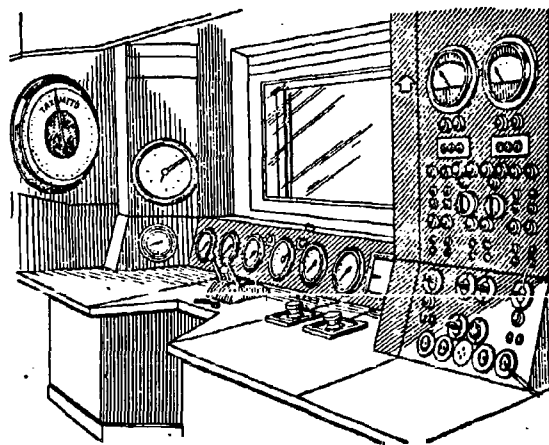
Fig. 110. Control panel.

Figure 110 shows a control panel. The control levers are situated in the central portion of the panel, and here we also find the buttons of the electrical starting system and the instruments which characterize [describe] the operation of the engine.

The instruments giving readings that must be recorded are located as close as possible to the central section, while the automatic recording instruments are situated somewhat farther away. Like instruments or instruments intended for the measurement of specific quantities must be grouped together. Instruments with particularly sensitive mechanisms must be mounted at points not subject to vibrations, on foam-rubber pads.

In the case of testing installations the control panel is kept at a rather great distance (4-6 m) from the engine. Under such conditions the transmission of movement from levers on the control panel to [corresponding] levers on the engine being tested presents some difficulty.

Remote-control transmission must provide for:

1) smoothness of stroke and absence of great friction;

2) tuning accuracy;

3) constancy of mutual position of control-panel lever and controlled lever;

4) insensitivity to vibrations and change in temperature of ambient medium;

5) rapid and easy connection and disconnection to and from levers, respectively.

Hinged coupling rods as well as cable, electrical, and hydraulic drives are used to achieve the link between the control-panel levers and the control units on the engine.

Operational experience has demonstrated that with careful adjustment and proper care all of the above-indicated types of driv func-
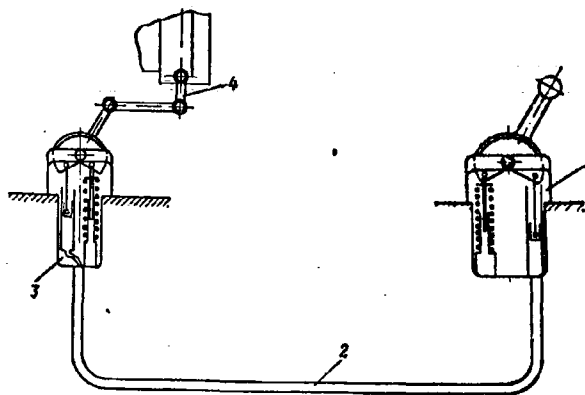
Fig. 111. Schematic diagram of hydraulic
drive. 1) Transmission element; 2) mani-
fold; 3) sensing element; 4) engine lever.

tion normally and provide for reliable engine control. It is true that
they do not all satisfy the above-enumerated conditions in identical
fashion or in complete measure.

Of the above-enumerated drives, the operationally reliable and
easily controlled hydraulic drives have gained rather extensive ac-
ceptance. In the use of cable transmissions we encounter difficulties
in the elimination of the free play that disturbs the precise tuning
of the engine to a given regime. Electrical transmissions restrict the
potentials of the test, since it is impossible to execute a nonuniform
shift of the control levers.

Figure 111 shows a schematic diagram of a hydraulic drive. The
drive consists of a transmitting and receiving [sensing] element, con-
nected to each other by means of a tube. The system is filled with
transformer oil or, if it is desired that the viscosity of the liquid
be reduced, the system is filled with a mixture of transformer oil and
kerosene. Each of the elements of the drive is fitted out with a pis-
ton that is spring loaded. Identical shifting of the transmission and
receiving elements is provided for in the system. Because of the ac-

- 183 -

tion of the springs the liquid is constantly under pressure.

The manifold between the transmission mechanism (on the panel) and the receiving [sensing] mechanism (on the engine or test stand) can be placed anywhere in the test section.

Signal lights (lights of various colors on the control panel) are widely used in the control rooms for convenience in servicing the installation during the test. Thus, for example, a signal light can indicate the flow of current to the installation, preparedness for engine start, fuel supply to the engine, etc.

The signaling systems (including the systems used for measurement purposes) are installed to correspond to the type of engine employed, as well as to match the testing installation and the manner in which the equipment has been positioned on the test stand.

The air in the control room should be changed at least every 10-15 minutes. It is recommended that the entire fuel-manifold system be enclosed in a special casing for which individual ventilation is provided.

4. TESTING INSTALLATIONS AND THEIR DISPOSITION AT THE STATION

Two types of testing installations are presently in use (Fig. 112). The basic difference between these installations lies in the disposition of the engine being tested in the test section with respect to the control panel and room. In the installation shown in Fig. 112a, the engine is positioned parallel to the control panel, while the engine is positioned perpendicular to the control panel in the installation shown in Fig. 112b. The test sections are structurally less complex in the first type of installation and satisfy the aerodynamic requirements in simpler fashion. Greater safety for the servicing personnel is ensured in the installations of the second type, since the rotation of the compressor, the turbine, and the propeller takes place

in a plane parallel to the control room. The location of the test in-
stallations at a station is based on the type of test installation
selected.
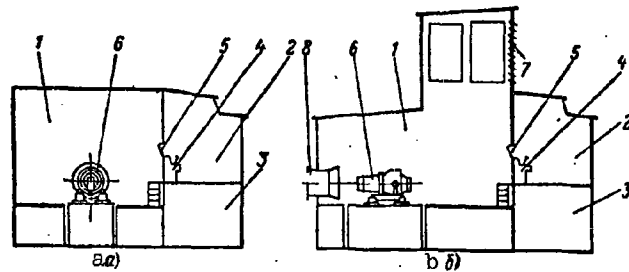
Fig. 112. Diagrams of testing installations.
1) Test section; 2) control room; 3) opera-
tional housing; 4) control panel; 5) observa-
tion window; 6) engine; 7) air inlet; 8)
ejector tube.
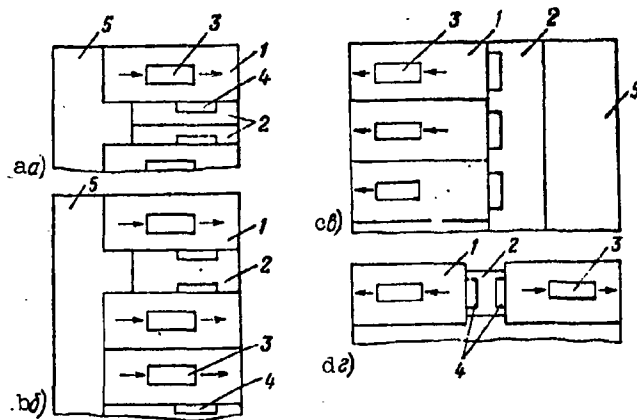
Fig. 113. Diagram of test-installation posi-
tion at station (arrows indicate direction of
air movement in test section). 1) Test section;
2) control room; 3) test stand with engine; 4)
control panel; 5) transfer point.

Figure 113 shows four versions of installation disposition. The
diagrams in Fig. 113a and b show stations with test sections in which
the engines are positioned parallel to the control panels, while the
remaining diagrams show stations with test sections in which the en-

- 185 -

gines are positioned perpendicular to the control panels. In some sta-
tions (Fig. 113a, b, and d) use is made of installations with individ-
ual control rooms (single-sided in Fig. 113a, and double-sided in Fig.
113b and d), while the remaining figures (Fig. 113c) show a joint con-
trol room.

The test sections of all testing installations must open on a
transfer point 5 in which the engine is prepared for the test and from
which the engine is sent on to the reassembly shop or the shipping
warehouse.

The diagrams in Fig. 113a, b, and c show a single-row disposition
of testing installations at a station, while the diagram in Fig. 113d
shows a double-row disposition. The single-row test-installation dis-
position facilitates the setting up of a station on the grounds of a
factory and makes possible centralized fuel supply, facilitates fire-
protection conditions, and also simplifies the supply of pure air to
the engines.

In addition to the above-mentioned basic buildings, a consider-
able portion of the area at a station is set aside for auxiliary ser-
vices. The area for the auxiliary structures is selected and allocated
on the basis of existing norms.

That portion of the station where the auxiliary structures are
located (the warehouses, the administrative offices, and the personnel-
servicing departments) must be set up in a two-story building. The sta-
tion area is generally set up at the edge of the plant grounds, next
to the assembly shop, the prevailing wind direction being taken into
consideration here. The exhaust gases should not be carried onto the
plant grounds. Railroad sidings should be available near the test sta-
tion in order to provide for the supply of fuel to the fuel storage
area. The shipping section to which the engines that have successfully

passed their tests are sent should be located close to the station.

5. TEST STANDS AND METHODS OF DETERMINING THRUST

The force of thrust must be determined with great accuracy. In measuring thrust the permissible error should not exceed $\pm 0.5\%$ of the magnitude of maximum thrust.

The various types of test stands should satisfy the following requirements:

1) they should exhibit sufficient mechanical strength and rigidity with relatively small dimensions and low weight;

2) they should produce no additional resistance to the approach of the air to the engine;

3) provide for reliable mounting of the engine and convenience of access to the engine for the purpose of performing the work associated with the servicing of the engine;

4) the design of the stands must permit of the testing of various modifications of a given type of engine;

5) guarantee sufficiently long service life.

The existing stands can be divided into fixed and movable. In the case of fixed stands the frame carrying the engine is not movable. Unlike these, the platform on the movable stands can shift within limits governed by stopping devices.

Determination of thrust on fixed stands

In tests carried out on fixed stands, engine thrust is determined by calculation on the basis of the following well-known formula (for the case, flight velocity $c = 0$)

$$R = \frac{a_b + a_t}{g} c_b + F_s (p_b - p_0).$$ (118)

Formula (118) shows that in order to determine the value of thrust it is necessary to know the area F_5 of the exhaust nozzle, as well as

- 187 -

the air flow rate G_v, the fuel flow rate G_t, the velocity c_5 of the gases at the outlet from the nozzle, the static pressure p_5 at the outlet from the nozzle, and the pressure p_0 in the test section. This method is complex and cumbersome; moreover, it is impossible to measure the air flow rate and the gas exhaust velocity with a high degree of accuracy. For this reason this method is rarely employed.

If the following values, known from the familiar gasdynamics formulas, are substituted into Expression (118)

$$G_s + G_r = G_r =$$

$$= F_5 \sqrt{ 2g \frac{k}{k-1} \left[\left(\frac{p_5}{p_6^\cdot} \right)^{\frac{2}{k}} - \left(\frac{p_5}{p_6^\cdot} \right)^{\frac{k+1}{k}} \right] \frac{p_6^\cdot}{\sqrt{RT_6^\cdot}}} \qquad (119)$$

and

$$c_5 = \sqrt{ 2g \frac{k}{k-1} RT_5^\cdot \left[1 - \left(\frac{p_5}{p_5^\cdot} \right)^{\frac{k-1}{k}} \right]} \qquad (120)$$

and if simple transformations are carried out, we will obtain an expression for the determination of thrust in the following form:

$$R = 2 \frac{k}{k-1} p_5 \left[\left(\frac{p_5^\cdot}{p_5} \right)^{\frac{k-1}{k}} - 1 \right] F_5 + F_s (p_5 - p_0). \qquad (121)$$

The value of the adiabatic exponent $\underline{k}$ in Expressions (119)-(121), a function of the composition of the gases and the temperature, can with a sufficiently high degree of accuracy be assumed to be constant.

The reaction-thrust value referred to the International Standard Atmosphere (MSA) is generally of interest in engine testing:

$$R_{np} = R \frac{1.033}{p_0}. \qquad (122)$$

Substituting the value of R from Formula (121) into Expression (122), we will obtain

$$R_{\text{пр}} = 1{,}033 \, \frac{p_5}{p_0} F_5 \left\{ 2 \, \frac{k}{k-1} \left[\left(\frac{p_6^*}{p_5} \right)^{\frac{k-1}{k}} - 1 \right] + \left(1 - \frac{p_0}{p_5} \right) \right\}. \qquad (123)$$

Thus in order to determine the value of the engine's reaction thrust, referred to the MSA, it is necessary to measure the mean total and static gas pressures at the outlet from the exhaust nozzle and the pressure in the test section, and then to employ Formula (123).

The values of the total and static pressures at the exit from the nozzle can be determined by means of three "rakes" mounted at angles of $120°$ to one another and connected by means of a common header for purposes of averaging. For the case in which the pressure $p_5 = p_0$, Formula (123) assumes the following form:

$$R_{\text{пр}} = 2{,}066 \, \frac{k}{k-1} \, F_5 \left[\left(\frac{p_6^*}{p_0} \right)^{\frac{k-1}{k}} - 1 \right]. \qquad (124)$$

The gasdynamic method on a fixed stand yields thrust measurements that are less accurate than those achieved with a dynamometer on a movable stand; however, these results are completely in accord with the technical requirements imposed on the release of series-produced TRD [turbojet engines].

Determination of thrust on movable stands

The method of measuring the force of thrust directly on movable stands has gained widespread acceptance. In this case the engine is mounted on a special platform or frame which can shift in the direction of the thrust developed by the engine. The platform shift is governed by a force-measuring device and ranges from 0.2 to 3 mm. The platform generally has its own stopping devices that restrict its motion.

All movable stands consist of a movable platform (frame) and a fixed base. In terms of structural indices, these stands can be divided into three basic groups: stands with a platform on rollers; stands

- 189 -

with a suspended platform; and stands on which the platform is fastened to flexible rods.
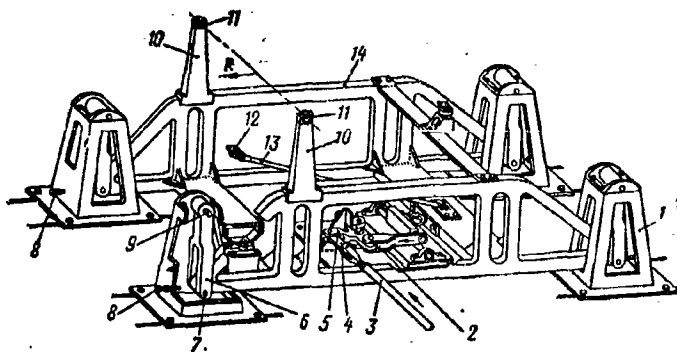
Fig. 114. Stand with suspended platform on con-
necting rods. 1) Support struts; 2) yoke; 3 and 4)
connecting rods; 5) Г-shaped lever; 6) connecting
rods; 7) lower pins; 8) stopping-device screw; 9)
pins; 10) movable-platform strut; 11) hinged sup-
port; 12) third-support unit; 13) lower-support
connecting rod; 14) movable platform.

The first widely used types of stands employed in the testing of air-reaction engines were units consisting of roller-mounted platforms. They were marked by their low sensitivity and poor stability of read-ings, because of the high contact stresses in the rollers and the rapid wearing out of their races. For this reason, roller-mounted platform stands are not used at the present time.

Suspended test-stand platforms can be suspended from the ceiling of the test section or from special support struts that are rigidly fixed to the foundation. The test-stands with platforms suspended from special support struts exhibit considerably greater operational advan-tages. Depending on the type of suspension, this category of test-stands can, in turn, be divided into two forms: test-stands with plat-forms suspended from connecting rods, and test-stands in which the platform is suspended from flexible strips.

A connecting-rod platform-suspension stand consists of four sup-
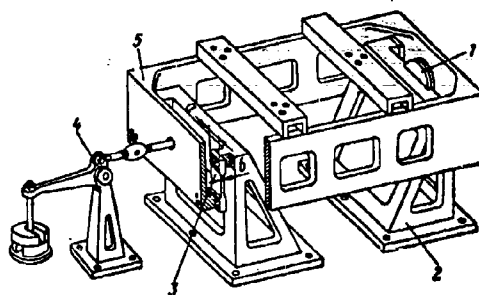
Fig. 115. Stand with suspended plat-
form on flexible strips. 1) Dynamom-
eter; 2) base; 3) flexible strip; 4)
device for calibration; 5) platform.

port struts 1 (Fig. 114) rigidly fixed to a special foundation; in ad-
dition, there is a movable platform 14 suspended from four connecting
rods 6, a thrust-transmission mechanism connected to the metering de-
vice, two struts 10, and supports 12 for the mounting of the engine on
the movable platform of the test-stand.

The use of spherical (self-stopping) bearings in the hinged sus-
pension joints permits the easy shifting of the platform upon applica-
tion of force. The upper head of the connecting rod is fitted with a
single bearing, while the lower portion of the connecting rod, made in
the shape of a yoke, is fitted with two bearings and is connected to
the eyelet of the platform 14 by means of pins 7. The magnitude of the
shift in the longitudinal direction is restricted by screws 8. The
lateral shifting of the platform during the course of engine operation
on the test-stand is limited by means of special stopping devices. The
lateral shifting of the platform permitted by the limiting devices
ranges from 0.1 to 0.3 mm.

The shifting of the test-stand platform in the longitudinal direc-
tion under the action of the force of thrust produced by the engine
being tested is of comparatively great magnitude (2-3 mm); with shift-
ing of this magnitude, the hose of the fuel system connected to the

- 191 -

engine, the fuel system being under high pressure during the course of the test, introduces distortions into the measurement accuracy. It is impossible to reduce the shifting of the platform, since it is impossible completely to eliminate the free play in the hinged connections of the test-stand.

The measurement accuracy for thrust is reduced also as a result of the lateral shifting and the friction that arises as a result between the guide bearing [a pillow] and the limiter.

Despite the indicated shortcomings, this test stand is occasionally used in testing series-produced VRD [air-reaction engines].

Figure 115 shows the diagram of a test stand in which the platform is suspended from flexible strips. The platform 5 is connected to the base 2 by means of four steel strips 3 attached to the platform supports and the base by means of stress-bearing bolts. The strips are specially thickened to provide for better attachment with the supports. When using a flexible strip exhibiting an a/b ratio of the order of 50, there is no lateral shifting of the test stand, thus increasing the accuracy of the thrust measurement. A test stand with strip suspension exhibits greater simplicity and support (strip) reliability than the test stand with connecting-rod suspension.

The shifting of the test-stand platform under the action of the force of thrust produced by the engine being tested must be small (to eliminate the effect of strip flexibility) and in contemporary installations does not exceed 0.5-1.5 mm.

In some test stands the platform is mounted on vertical flexible rods and the shifting of the platform is limited to 0.2-0.5 mm. Because of this small shift, the accuracy in the determination of thrust is increased.

These test stands are quite simple and they are expediently em-

ployed for engines of small weight.

Of the above diagrams for test stands used to determine thrust, the greatest acceptance has been gained by those stands in which the platforms are suspended from flexible strips.

Test-stand calibration

In order to achieve more exact thrust readings, it is recommended that the movable platform on all types of test stands be prestressed. It is advisable for this purpose to provide for a tension-lever device which can simultaneously serve as the calibration unit.

The test-stand platforms have been equipped with special devices which serve to hold the engine, i.e., engine support frames. The engine-support frames are absent in certain types of test stands, the engines being mounted directly to special units on the platform.

The mounting elements are designed so as not to restrict the freedom of engine movement after the starting of the latter, in view of the thermal expansion of certain engine component parts. The engine is mounted to the test stand at three points.

To maintain the thrust measurement accuracy, all connections to the engine supply and control elements are made of elastic materials. It is impossible to achieve absolute accuracy in the measurement of thrust, because of the presence of frictional forces in the measurement system and because of the influence exerted by the various connections. In this connection it is necessary to calibrate the test stand together with the measuring device with which it is to carry out its function.

The test stand is calibrated at a time when an engine is mounted on it. There are two types of calibration, i.e., static calibration in the case of an inoperative engine, and dynamic calibration for the case of an engine in operation. Only rarely is a test stand calibrated
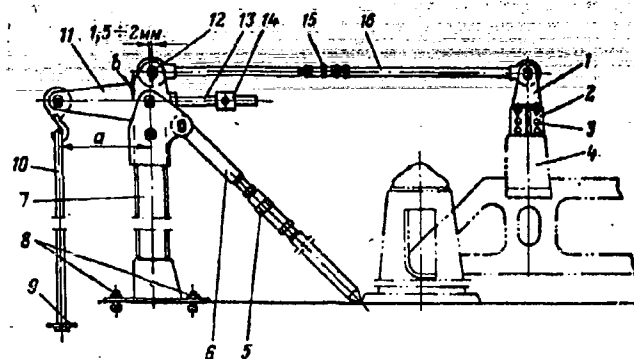
Fig. 116. Device for calibration of test
stands. 1) Yoke; 2) bracket; 3) bracket fasten-
ing bolts; 4) strut for movable platform of
test stand; 5) turnbuckle; 6) stops; 7) strut
of calibrating device; 8) strut-fastening
bolts; 9) weight holder; 10) rod; 11) Γ-shaped
lever; 12) pin; 13) lever; 14) movable counter-
balance weight; 15) turnbuckle; 16) connecting
rod.

for dynamic operation; for this reason we will not consider dynamic
calibration here.

Special devices installed temporarily alongside the test stand,
or the tension-lever devices included in the designs of some test
stands, are used for purposes of calibration. The calibration device
is used artificially to reproduce a load on the test stand that cor-
responds to the direction of engine thrust. The calibration devices
may exhibit variation in design and operating principle. The simplest
and most commonly used devices in testing practice are the lever-type
calibration units.

Figure 116 shows a calibration lever-type device whose two struts
7 are attached by means of bolts 8 to the foundation on the two sides
of the stand. The vertical position of the struts is controlled by
stops 6 through the turnbuckle 5. Γ-shaped levers 11 are connected to
the upper portion of the struts by means of a hinge attachment; these
levers are connected by means of pins 12 to connecting rods 16 which

- 194 -

have been provided with turnbuckle 15. At the other end of the levers
pan 9 is suspended from rod 10 to hold the calibration weights. The
other end of the connecting rod is linked to struts 4 of the moving
test-stand platform through yoke 1 of bracket 2. A counterbalance 14
is attached to lever 13 which represents a continuation of lever 11.
In setting up this calibration device, the length of the connecting
rod 16 is controlled by means of the turnbuckle so that the axis of
the pin 12 connecting the connecting rod with the lever shifts toward
the engine by some 1.5-2 mm with respect to the axis of the pin con-
necting the lever to the strut of the unit (the lengths of the connect-
ing rods must be identical in this case). Then the rods with the weight
pans are suspended and the indicator of the test-stand measuring de-
vice is set to "0" by shifting weights 14 on levers 13.

Loads ranging in weight from 10 to 25 kg are placed on the pan 9
for purposes of calibrating the test stand and the readings of the
scale are recorded in the calibration log. The loads are successively
increased and the readings of the thrust-measuring device are recorded.
The maximum load must exceed the maximum thrust developed by the en-
gine by 10-15%. In this case it is necessary to take into considera-
tion the relationship between arms a and b of lever 11.

For purposes of verifying the sensitivity of the test stand, equal
weight fractions are added to the two weight pans, these weights cor-
responding to 0.5% of the measured or maximum thrust (which depends on
the actual technical conditions). If the thrust-measuring device does
not indicate a change in reading upon the addition of such a weight,
the calibration device must be unloaded and the device must be checked
to make certain that there are no blocks within the elements [links]
of the test stand, the device, or the measuring unit. Any detected de-
fects must be eliminated, and the calibration of the test stand must

be repeated.

Upon completion of the loading of the calibration device, the latter is unloaded by the gradual removal of the weights from the weight pans. During this procedure the readings of the measuring device are recorded for the calibration points at which the earlier readings were determined, as the weights were being increased.

If the thrust-measurement unit readings at the analogous points obtained during the loading and unloading of the calibration device exhibit a divergence in excess of $\pm 0.5\%$ from the maximum (or occasionally the measured) thrust, the stand, the calibration device, and the measuring unit must be checked out and the calibration must be repeated.

After the complete removal of the weights from the calibration device, the movable platform of the test stand must be rocked back and forth and given an opportunity to find its equilibrium position. The indicator of the measuring unit must indicate a zero thrust value at this time. Upon completion of the calibration, a calibration graph for the test stand is prepared on the basis of the mean data derived during the loading and unloading of the calibration device.

A test stand must be calibrated at least once a month, as well as prior to and after extensive engine testing and after each overhaul of the stand. Depending on the construction of the stand, the nature of the tests that have been carried out, and the design of the calibra- .
tion unit, the calibration procedure may exhibit certain unique features in connection with which the sequence of calibration is laid down in the corresponding technical instructions.

6. TEST STANDS AND TORQUE-DETERMINATION METHODS

The basic parameter that characterizes the efficiency of turbo-prop engines is the power absorbed by the propellers. The direct measurement of this power during the course of a test would be inefficient.

The effective power is generally determined by an indirect method in accordance with the following formula:

$$N_e = \frac{M_{кр}n}{716,2}.$$ (125)

In determining the power of turboprop engines it is necessary to devote particular attention to the methods and accuracy of determining torque. The permissible error according to existing technical requirements should not exceed $\pm 0.5\%$ of the magnitude of the maximum value of the torque being measured.

The torque-determination methods used at testing stations vary. But in all cases, the engine being tested is mounted on a rigid [fixed] (with a nonmoving platform) or a movable balance test stand (with a rocking platform).

The requirements imposed on the above-indicated test stands are identical to the above-mentioned requirements imposed on the test stands for the determination of reaction thrust.

Regardless of the type of stand on which a turboprop engine is being tested, a necessary element of the test stand is the brake which absorbs the engine power.

Air and hydraulic brakes have found considerable application in the testing of turboprop engines. Engine propellers are used as air brakes. Air brakes are used to test engines both on fixed as well as on balance test stands. Hydraulic brakes are used only for engine tests conducted on fixed test stands.

Let us now undertake an examination of the various methods of determining the torque of a turboprop engine.

Turboprop-engine tests on fixed test stands with propellers and hydraulic brakes

Figure 117 shows a test stand consisting of a rigid space girder, placed in the foundation and supporting the stress-bearing frame 2

- 197 -

which contains the engine framework 1 in which is mounted the engine whose power is absorbed by a propeller. The test stand is simple in design, easy to operate, and designed for the testing of engines of great power. The testing of engines of lower power is possible through some simple adjustments of the test stand, i.e., by mounting an intermediate frame on the stress-bearing ring.
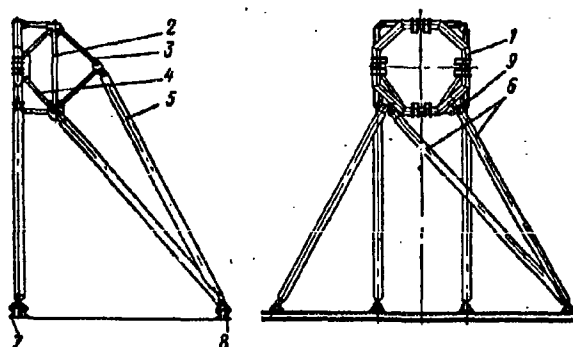
Fig. 117. Rigid test stand for testing TVD [turboprop engines] with propeller. 1) Engine mount frame; 2) stress-bearing frame; 3, 4) braces; 5, 6) struts; 7, 8) support points; 9) pins.

It is possible to use a variable-pitch propeller as the brake for this type of engine, if the characteristic of the latter is circumscribed by the area OABO (Fig. 118). The line OA corresponds to the maximum value of the blade angle Ψ_{max}, while the line OB corresponds to the minimum value of the blade angle Ψ_{min}. The point A corresponds to the maximum torque. The point B sets the limit for the maximum permissible revolutions from the standpoint of propeller strength. The line AB characterizes the change in power at $M_{\kappa\tau} = $ const.

In principle, knowing the relationship between the power absorbed by the propeller and the revolutions for the various values of $\Psi = $ = const makes it possible to determine engine power. But in actual practice this method is rarely used, since the characteristics of the
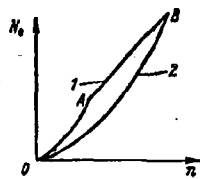
Fig. 118. Characteristic of variable-pitch propeller. 1) For a "heavy" propeller; 2) for a "lightened" propeller.
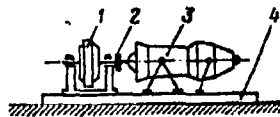
Fig. 119. Diagram of the mounting of a TVD [turboprop engine] on a fixed test stand with a hydraulic brake used to absorb the engine power. 1) Brake; 2) sleeve joint; 3) engine; 4) test stand.
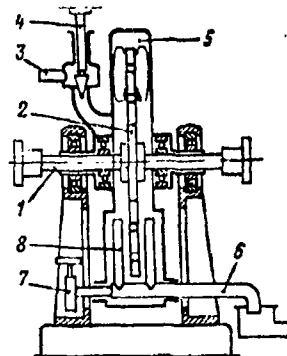
Fig. 120. Schematic diagram of hydraulic brake. 1) Shaft; 2) brake disk; 3) water feed; 4) valve; 5) stator casing; 6) drain; 7) worm gear; 8) turning connection tubes.

propeller in operation in the test section are not stable and cannot be derived with a sufficient degree of accuracy.

The magnitude of the torque on the shaft of the engine being tested in a fixed test stand where propellers are used as brakes can also be determined by means of special torquemeters (IKM) (see Chapter 3).

Hydraulic brakes have gained considerable acceptance for purposes of absorbing and measuring power. Figure 119 shows the diagram of the mounting of a turboprop engine 3 on a fixed test stand 4, a hydraulic brake 1 being used as the power absorber. The test stand consists of a rigid girder mounted on a special foundation.

The operating principle of the hydraulic brake is based on the utilization of the resistance that arises in the rotation of disks in a fluid. The schematic diagram of such a hydraulic brake is shown in Fig. 120. Shaft 1 carries brake disk 2 rotating within the casing of stator 5 which can turn in its bearings. Water supplied through valve 4 moves through tube 3 under constant pressure to the center of disk 2, whence under the action of centrifugal forces it is ejected to the periphery of the disk. The waste water is removed

- 199 -

through tube 6. The thickness of the water layer inside the casing and, consequently, the power absorbed by the brake, is regulated through connection tubes 8 which are turned by means of worm gear 7.

The hydraulic resistance acting on the disk as it moves through the layer of water produces a braking moment. The latter is directed against the rotation of the disk and balances its equal but oppositely directed torque, the latter being applied to the shaft of the brake. The work performed by the engine is converted into the heat which raises the temperature of the water.

The moment equal to the braking moment, but oppositely directed, is applied through the water to the casing. This moment will turn the casing in the direction of rotor rotation. The magnitude of the moment is measured by means of dynamometers. Thus the hydraulic brake is used to measure torque.

Turboprop engines can be tested on a hydraulic-brake test-stand with or without a reduction gear. Low-power engines operating with a single propeller are tested with a reduction gear.

The following requirements are imposed on hydraulic brakes used in TVD [turboprop-engine] tests:

1) reliable operation for no less than 2000 hours;

2) the error in the torque measurement must not be greater than ±0.5% of the maximum measured moment;

3) provision must be made for changing the load within wide limits at a constant number of revolutions;

4) the brake must be simple to operate and easy to control.

With a high theoretical number of revolutions, the hydraulic brake for the testing of powerful TVD is quite compact and light.

The above-enumerated requirements can be satisfied by the domestically produced GT-E hydraulic brake (Fig. 121). The hydraulic por-
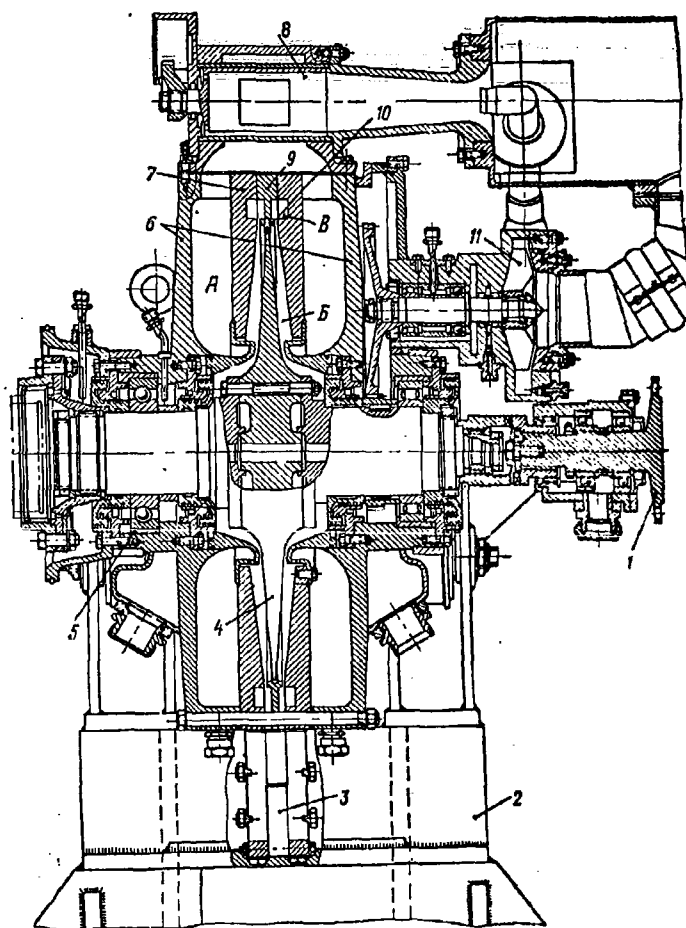
Fig. 121. GT-E hydraulic brake. 1) Freewheeling
coupling; 2) support; 3) drain fitting; 4) disk;
5) bearings; 6) support flanges; 7) casing disks;
8) slide valve; 9) middle disk; 10) settling ring;
11) water pump; A) Fill chamber; B [Б]) decelera-
tion chamber; C [B]) settling chamber.

tion of the frame consists of a fill chamber A, a deceleration chamber
B [Б], and a settling chamber C [B]. The fill chamber is a cavity from
which water flows into the deceleration chamber; the purpose of the
fill chamber is to even out the fluid pressure, which is extremely im-
portant from the standpoint of the operational stability of the brake.

Mechanical energy is converted into thermal energy in the deceleration chamber. The deceleration chamber is closed off on the outside by means of ring 10 of middle disk 9. Slots for the passage of water from the deceleration chamber to the settling chamber are formed between the ring and the frame disks 7. On the stator surfaces facing the brake disk there are radial fins [extended surfaces] to raise the resistance coefficient of the deceleration-chamber walls.

During the course of the operation air and water vapor accumulates in the deceleration chamber, and this produces shaking and unstable operation of the hydraulic brake. To eliminate this defect the deceleration chamber is opened to the atmosphere. Water passes into the brake through a flexible hose from a constant-level chamber through slide valve 8 controlled by means of an electric motor. In other words, the slide valve serves to control the magnitude of the power absorbed by the brake.

The water pump 11 supplying the ejector of the hydraulic brake is mounted on the stator. Since the pump 11 is driven by the shaft of the brake and is mounted on the stator housing, it [the pump] exerts no influence on the accuracy of power measurement. The ejector provides for the stable operation of the hydraulic brake in all regimes.

To avoid the formation of scale, the temperature of the water leaving the hydraulic brake must not be permitted to exceed 70-80°C.

The accuracy in the measurement of torque is a function of the magnitude of friction at the supports and of the rigidity of the tubing through which the water flows. The smaller the turning of the stator, the higher the measurement accuracy. The tubing (hoses) must be soft.

The torque acting on the stator is transmitted to the measuring device. Two levers (Fig. 122) are attached to the hydraulic-brake
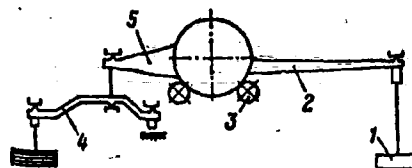
Fig. 122. Diagram of calibra-
tion device and measurement of
torque. 1) Dynamometer; 2) op-
erating lever; 3) rollers; 4)
calibration device; 5) cali-
bration lever.

frame. The calibration lever 5 serves to absorb the forces from the
weights positioned in the calibration device 4. The operating lever 2
transmits the forces resulting from the reaction moment to dynamometer
1.

The dimensions of the hydraulic-brake disk are selected on the
basis of calculation. Considering the friction of water on the two
sides of an infinitely small annular brake-disk element and integrat-
ing the differential equation, we will obtain the following formula
for the determination of the power of the disk friction:

$$N_x = \frac{\varphi n^3 (r_x^5 - r_v^5)}{C},\qquad(126)$$

where φ is the coefficient which characterizes the influence of the
friction of the disks in the fluid on the magnitude of the losses; r_n
and r_v are, respectively, the outside and inside radii of the brake
disks, in m; $\underline{n}$ represents the number of brake-rotor revolutions, in
seconds; C is a constant.

The design of the GT-E hydraulic brake was carried out in accord-
ance with the semi-empirical formula

$$N_x = C_x \left(\frac{2a}{1+a}\right)^{1,8} \left(\frac{v}{2}\right)^{0,2} \frac{\pi \rho \omega^{2,8} (r_x^{4,8} - r_v^{4,6})}{1380},\qquad(127)$$

where C_d is a constant characterizing the resistance of the disk (for
the GT-E brake, $C_d = 0.209$); a is a constant characterizing the influ-

ence of the fins on the walls of the frame disks on the magnitude of the absorbed power (for the GT-E hydraulic brake it is assumed that $\alpha = 5$); ω is the angular velocity of the disk, in 1/sec; ν is the coefficient of the kinematic viscosity of the working fluid, in m^2/sec; ρ is the density of the working fluid, in $kg \cdot sec^2/m^4$.
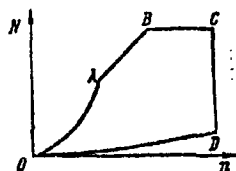
Fig. 123. Hydraulic-brake characteristic.

The quantities ν and ρ are determined from the mean temperature of the water at the inlet to and outlet from the brake, and this temperature is usually $t_{sr} = 40-45°C$. By using Formula (127) we can construct the characteristic of the hydraulic brake for the case in which it is completely filled, i.e., maximum power as a function of the number of revolutions.

The calculated power is used to determine the flow rate of water through the hydraulic brake:

$$Q = \frac{632 \cdot N_x}{\Delta t},\qquad (128)$$

where Δt is the temperature difference for the water between the inlet to and the outlet from the brake, generally equal to $\Delta t = 35-45°C$.

The quantity Q is used to calculate the cross section of the tubing at the inlet to the hydraulic brake. It is recommended that the speed of the water in the tubing be set to range between 2-3 m/sec. The quantity Q is also used to calculate the flowthrough passages of the throttle, the water pump of the ejector, and the drain fittings. The maximum pressure in kg/m^2 developed in the deceleration chamber is calculated from the following expression:

$$p_{max} = \frac{\rho}{2}(r_s^2 - r_s^2)\left(\frac{\omega}{1+\alpha}\right)^2.\qquad (129)$$

The force applied against the wall of the deceleration chamber can be found from the developed pressure.

Figure 123 shows the characteristic of a hydraulic brake. If the characteristic of the engine being tested falls within the area circumscribed by the lines OABCDO, this would be an indication that the given brake can absorb the power of the engine and measure the magnitude of the torque. The initial segment (OA) of the characteristic corresponds to the functioning of the brake when filled with water to the maximum and this segment is a curve that is close to being a cubic parabola.

The torque attains its maximum value at point A. A further increase in the number of brake revolutions is permissible if the thickness of the water layer in the brake is reduced so that the torque remains constant on the segment AB and equal to its maximum value.

The power absorbed by the brake attains its maximum at point B. A further increase in this power results in the onset of the boiling of the water filling the brake. The limit angular velocity of the brake rotor is attained at point C.

The line OD of the characteristic indicates the minimum power absorbed by a brake without water because of the friction in the rotor bearings and the friction between the disk and the air.

The hydraulic brake with a torquemeter is calibrated by means of a calibration device consisting of levers, connecting rods, and weights; a diagram of such a device is shown in Fig. 122. The method involved in the calibration of a hydraulic brake is analogous to the method used to calibrate the thrust-measurement test stand. The accuracy requirements for the calibration of a hydraulic brake are the same as in the case of the measurement of reaction thrust.

A hydraulic brake is calibrated at intervals stipulated in the technical documentation for the testing of a given type of engine, and after all, overhauls are preventive-maintenance inspections.
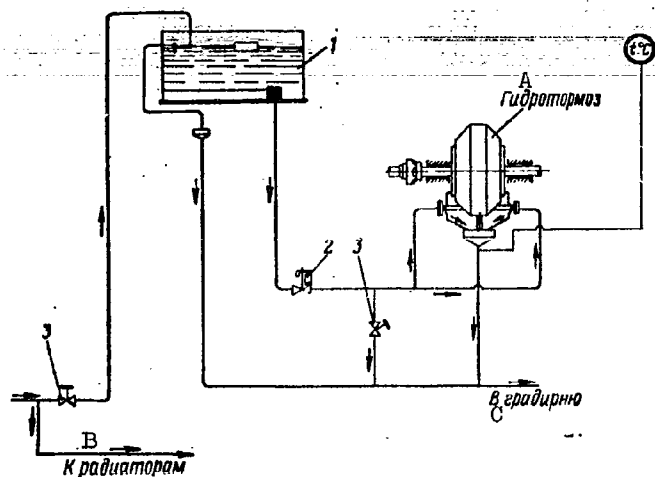
Fig. 124. Hydraulic system of the installation.
1) Constant-level tank; 2) slide valve with electric motor; 3) valves. A) Hydraulic brake; B) to radiators; C) to cooling tower.
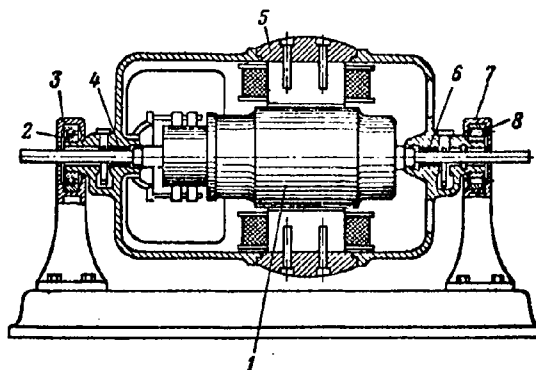
Fig. 125. Balancing electric motor. 1) Armature; 2, 8) stator bearings; 3, 7) struts; 4, 6) rotor bearings; 5) stator.

A shortcoming of hydraulic brakes in the testing of powerful engines having coaxial propellers is the fact that it is necessary to remove the reduction gear, as a result of which the engine power is determined without any consideration of the losses in this unit.

The application of a hydraulic brake as the absorbing device for

the power developed by the engine being tested results in the addition of yet another system — a water system — to all of the systems of the test installation; a schematic diagram of this water system is shown in Fig. 124. The water from a main enters the constant-level tank 1 whence it passes into the brake through a filter and a controlled slide valve 2. The waste water, as well as the excess water from tank 1, is passed on to the cooling tower where it is cooled, subsequent to which it is returned to the constant-level tank. The system is not complex, but during the testing of powerful engines it must exhibit great flowthrough capacity.

In tests on engines with an air or hydraulic brake, a balancing electric motor is occasionally used as a starting device (Fig. 125). The balancing electric motor makes it possible simultaneously with the turning over of the engine being started to determine the magnitude of the power absorbed by the engine during the starting procedure. The moment applied to the stator of the electric motor is measured in the same manner as in the case of a hydraulic brake, by means of levers and a measuring device. After the engine has entered into its regime of operational revolutions, the balance electric motor is shut off.

Figure 126 shows a rigid test stand for the testing of TVD [turbo-prop engines] with propellers acting as brakes, and with a balance electric motor 6 functioning as the starter. The figure shows dynamometer 9 serving for purposes of determining the magnitude of the power absorbed by the engine at the instant of start and the calibration device 7 of the balancing electric motor.

Engine tests on balance test stands

The power of a turboprop engine can be determined by means of a balance test stand. The propeller serves as the brake to absorb the engine power.
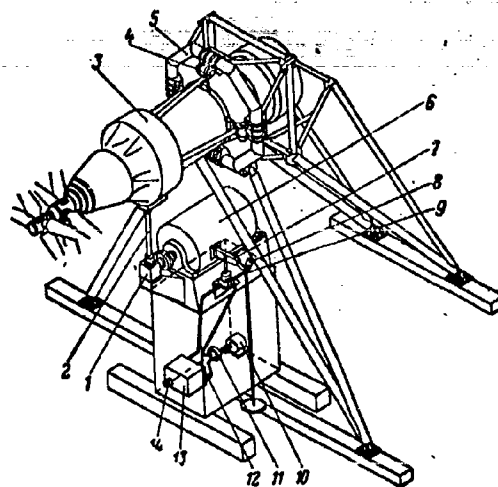
Fig. 126. Rigid test stand for the
testing of TVD [turboprop engines]. 1)
Reduction gear; 2) connecting shaft;
3) engine; 4) dashpot; 5) test stand;
6) balancing electric motor; 7) device
for the calibration of the balancing
electric motor; 8) manometer; 9) dyna-
mometer; 10) electric motor; 11) pump;
12) filter; 13) fuel tank; 14) elec-
tric heater.
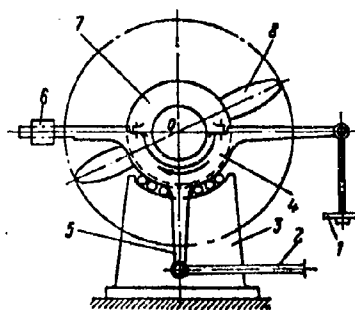
Fig. 127. Schematic dia-
gram of balance test
stand. 1) Calibration de-
vice; 2) connecting-rod
system; 3) immovable base;
4) frame; 5) lever; 6)
adjustable load; 7) en-
gine; 8) propeller.

Figure 127 shows a schematic dia-
gram of a balance test stand. The test
stand consists of a fixed base 3 and a
frame 4 that rocks about the 0 axis. The
engine 7 being tested is mounted on the
frame. During engine operation propeller
8, rotating counterclockwise, produces a
clockwise reaction moment on the rocking
axis of the frame. The reaction moment
is equal in magnitude to the torque ap-
plied to the shaft of propeller 8 and it
causes the frame and lever 5 which actu-

- 208 -

ates connecting rod 2 linked with the torquemeter to turn through a certain angle. The calibration of the test stand by means of device 1 is carried out in a manner analogous to the calibration of the test stands used for the measurement of thrust.

An absolute necessity in the case of balance test stands is the positioning of the center of gravity of the rocking system beneath the rocking axis. The axis of the engine is generally made to coincide with the axis of the rocking system or it is positioned somewhat higher.

The twisting of the flow streamlining the engine by means of the propellers exerts some influence on the accuracy with which the torque M_{kr} is measured. The twisted airstream reduces the actual torque by 2-3%.

It is well known that gases are exhausted axially from a turbine only in the case of engine operation in the rated regime. Analysis of experimental material shows that the twisting of the gas stream leaving the turbine may introduce an error as high as 10% of the measured magnitude of M_{kr}.

In order to eliminate the influence of the streamlining of the engine with an airstream twisted by the propellers, it is recommended that the engine be covered during the course of the test with a rapidly removable cowling made of sheet steel and fastened to the fixed base, or that a guide-vane assembly be installed between the engine and the propeller.

In order to eliminate the influence of a twisted gas stream behind the turbine on the measurement of M_{kr}, it is recommended that a guide-vane assembly be installed at the outlet from the exhaust nozzle of the engine, this assembly being mounted in a cradle.

After implementing the above-indicated measures, it becomes possible to measure the torque of a TVD [turboprop engine] with an error

- 209 -

not exceeding ±2%.

As can be seen from the above, the accuracy of torque measurements in engine tests on balance stands does not correspond to the technical requirements.

The greatest measurement accuracy for torque is achieved by the hydraulic brake. The testing of engines on rigid test stands with air brakes and IKM [torquemeters] for the determination of the magnitude of M_{kr} is the most promising.

7. STANDS FOR THE MEASUREMENT OF THE EQUIVALENT POWER OF A TVD [TURBO-PROP ENGINE]

The efficiency of a TVD [turboprop engine] is evaluated by the equivalent power which represents the sum of the effective power applied to the shaft and the power produced by the reaction thrust. Under test-stand conditions, this power can be determined from the following expression

$$N_{s} = N_{e} + 0.91 R_{c}. \qquad (130)$$

where 0.91 is the factor used to convert thrust into power; N_e is the effective power; R_s is the reaction thrust of the nozzle.
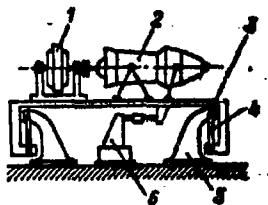
Fig. 128. Test stand for the determination of equivalent power. 1) Hydraulic brake; 2) engine; 3) movable platform; 4) flexible strip; 5) base; 6) dynamometer.

Thus in order to determine N_e it is necessary simultaneously to measure the torque M_{kr} and the nozzle reaction thrust R_s.

The stand for the determination of equivalent power consists of elements which make it possible to carry out the simultaneous and separate measurement of torque and thrust.

Equivalent power can be determined whether the engine is installed on a fixed or a movable test stand. In this case it is expedient to determine reaction thrust on a fixed test stand by employing
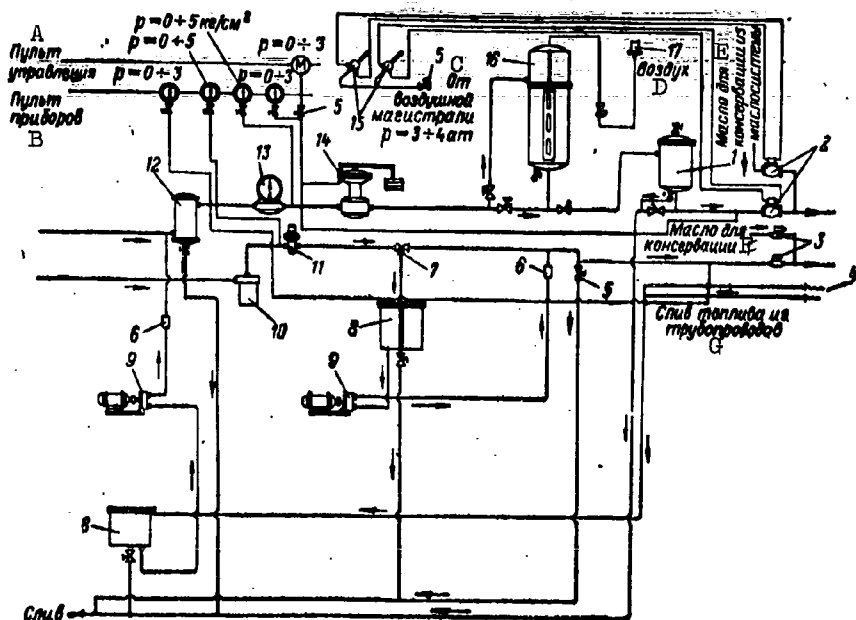
Fig. 129. Diagram of test-station fuel system. 1) Filter; 2, 3) pneumatic valve; 4) flexible hoses; 5) valve; 6) reverse valve; 7) three-stroke valve; 8) metering tank; 9) pump unit; 10) purification filter for starter fuel; 11, 14) automatic pressure regulator; 12) coarse fuel-purification filter; 13) fuel-flow-rate counter; 15) compressed-air valve; 16) sampler; 17) emergency fire-safety device. A) Control panel; B) instrument panel; C) from air manifold; D) air; E) oil for protection, from oil system; F) oil for protection; G) fuel drain from manifold.

the gasdynamic method, while it is best to determine the torque by means of one of the above-considered methods.

The stands in which the engine and the hydraulic brake which absorbs the power of this engine are mounted on a movable platform have found some application for purposes of determining equivalent power. The diagram of such a test stand is given in Fig. 128. A platform 3 is suspended on strips 4 from base 5. The engine 2 whose power is absorbed by hydraulic brake 1 is mounted on the platform. The thrust developed by the gas stream leaving the exhaust nozzle is measured by dynamometer 6. This method provides high accuracy in the determination of

both the thrust of the exhaust nozzle and the engine torque. This installation is cumbersome, complex, and not always efficient.

The calibration of the dynamometers used to measure thrust and torque on the test stands considered above is carried out separately, but with the engines mounted and fitted out to correspond to the equipment being used.

8. THE SYSTEMS OF THE TESTING INSTALLATION

In order to make it possible to carry out engine tests and to record the characteristics stipulated in the technical manuals, testing installations are fitted out with fuel and oil systems, fuel-charging systems, starting systems, etc. Let us examine some of these systems.

The fuel system

A fuel system for an installation employed to test VRD [air-reaction engines] must provide for:

1) uninterrupted supply of the required quantity of fuel to the engine for all operating regimes;

2) the possibility of rapid measurement of fuel flow rates in all engine-operating regimes, with an error not to exceed $\pm 0.5\%$;

3) careful separation of air and filtration of the fuel supplied to the engine;

4) supply of two various grades of fuel (starter and main) to the engine at various instances;

5) convenience in operation and airtight construction.

The fuel is fed to the engine through a flow tank situated on the testing installation, or it is supplied directly from the fuel storage area. Contemporary VRD [air-reaction engines] expend considerable quantities of fuel. For this reason virtually all testing stations employ a system of direct fuel supply to the engine from a central storage area. The fuel is supplied through tubing exhibiting cross sections

- 212 -
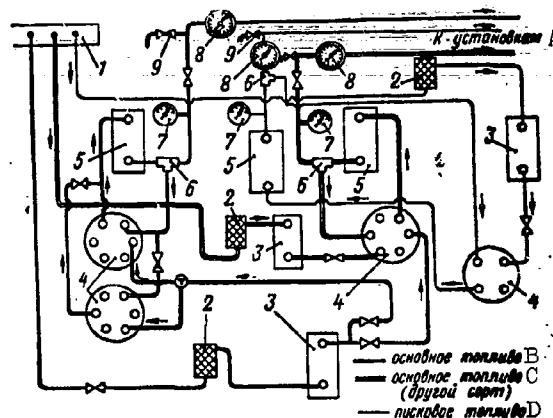
Fig. 130. Diagram of central fuel storage. 1) Entry point; 2) filters; 3) pump; 4) containers; 5) pressure pump; 6) reduction valve; 7) manometer; 8) flowmeters; 9) valve. A) To the installations; B) main fuel; C) main fuel (another grade); D) starter fuel.

adequate for the continuous supply of several operating engines, and the fuel pressure in the system is kept equal to 1-1.5 atm excess [gauge pressure].

A schematic diagram of an installation fuel system in which the fuel is fed continuously is presented in Fig. 129. The main fuel from the central fuel storage area is fed through a coarse-purification filter 12. Then the fuel is passed through the total fuel flow-rate counter 13 to the automatic pressure regulator 14 which maintains the required pressure in the net. The fuel is directed from the regulator to the engine through flowmeter 16, the latter being of the volumetric or weight type. The fuel enters the engine through filter 1 and pneumatic valve 2. The pneumatic valve is designed to shut off the fuel in the case of a fire emergency. It is advisable to install a rotameter between the flowmeter 16 and filter 1, thus making it possible continuously to monitor the magnitude of the flow rate and to maintain the

- 213 -

stability of the engine operating regimes.

The starter fuel is supplied to the engine through filter 10, the automatic pressure regulator 11, and the emergency electromagnetic remote-controlled valve 3. The metering tank 8 is used to measure the flow rate of the starter fuel. There must be a drain manifold in a fuel system to provide for the return of the excess fuel into the fuel storage area.

The adopted centralized supply of the installations with fuel provides for the continuous movement of fuel to the engines and it also provides for fire safety. The fuel storage area generally consists of flow tanks, a pump station supplying the fuel to the installations, and a "drain" station which pumps the fuel from the railroad tank-cars into the fuel tanks at the fuel storage area. Three pipelines are used to supply the fuel to the installations: main fuel (various grades) is moved through two of these pipelines, while the starter fuel is moved through the other. There is an individual pump providing the required excess pressure in each pipeline. The constancy of pressure in the system is maintained by reduction valves which provide for the bypass of excess fuel back to the fuel tanks.

Figure 130 shows a diagram of an approximate disposition of fuel tanks and equipment at a central fuel storage area, the fuel being supplied to the installations by means of pumps.

The fuel entering the engine is carefully purified. The installation of two filters is generally provided for in a fuel system, i.e., a coarse-purification filter and a fine-purification filter. The filters included in the system must exhibit low coefficients of hydraulic resistance and they must trap particles larger than 5 μ in size.

Silk (capron) fabric or special rubberized paper is used as the filtering material. The construction of one such filter is shown in
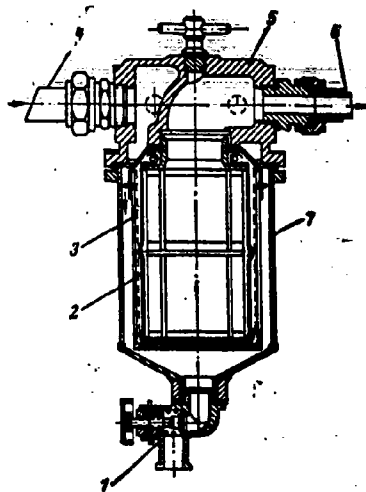
Fig. 131. Fuel filter. 1) Drain valve; 2) silk; 3) frame of filtering element; 4) fuel-supply connection tube; 5) upper cover plate; 6) fuel-removal connection tube; 7) housing.

Fig. 131.

The choice of the filtering-surface area depends primarily on the magnitude of the fuel flow rate, the permissible resistance of the filter, and on the proposed frequency of overhaul.

The hermetic sealing of the valves for a pressure greater than the operating pressure is checked systematically.

The cross-sectional area of the fuel manifold [pipeline] is selected so that the fuel moves at a speed of 1-2 m/sec. To reduce possible losses in pressure, the radii of curvature are generally made to exceed three diameters of the manifold.

All manifold connections must be easily accessible for inspection and rapid replacement. In order to eliminate the influence of the fuel-supply tubing on the measurement of thrust or engine torque (when testing engines on nonrigid test stands), the fuel manifold is connected to the engine by means of a flexible hose directly at the test stand.

The hermetic sealing of the fuel system under a pressure greater than the normal operating pressure is checked no less than twice and no more than once a month [sic].

The oil system

Contemporary turbojet engines are equipped with an oil system that is independent of the aircraft (autonomous), and its individual elements (containers, radiators, etc.) are structurally incorporated as part of the engine. Therefore, for the series-production testing of

engines no external oil-circulation system is required at the installation. The TRD [turbojet engine] testing installations are generally fitted out only with an oil system intended for the protection of the engine.

For purposes of cooling the rubbing component parts of a TVD [turboprop engine] reduction gear, considerably more oil must be pumped through than in the case of a TRD [turbojet engine] and an external oil system satisfying the following requirements is therefore required at TVD [turboprop-engine] testing installations.

1) the system must provide for the supply of the required quantity of oil to the engine, as well as for the measurement of the quantity and flow rate of oil being pumped;

2) the oil leaving the engine must be cooled, and the temperature at the inlet to the engine must be maintained within certain limits;

3) the oil leaving the engine must be filtered;

4) prior to starting the engine under conditions of low ambient-air temperatures, provision must be made for the heating of the oil.

Figure 132 shows the schematic diagram of an oil system for a TVD [turboprop-engine] testing installation. The oil is fed from a special container into tank 4 set up on a weighing device 5 through oil flow-rate indicators 7. The oil-tank enclosure is generally designed to provide for the supply of two grades of oils to the testing installations and for the return of the waste oil from these installations. Tank 4 is equipped with an electric heater. From the tank the oil is fed through a filter to the engine. As the oil leaves the engine it passes through filter 10 (made of a brass grid) and returned to the tank through the flowmeter 2 which makes it possible to determine the quantity of oil being pumped through. The system has a water-oil radiator 1 by means of which it is possible to determine the heat transfer to

the oil.

Two filters connected in parallel at the outlet from the engine make it possible to switch off one of the filters and to carry out an inspection without stopping the test. The pump unit 3 makes it possible to heat the oil in the entire system. In order to achieve this the system must provide, in advance, for the completion of the circuit by means of valves 12.
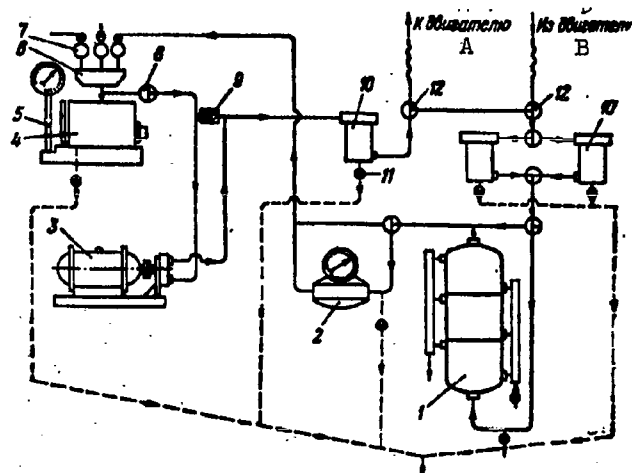
Fig. 132. Schematic diagram of oil system. Conventional denotations: — oil feed; -- oil drain; ~ flexible hose. 1) Water-oil radiator; 2) flowmeter; 3) pump unit; 4) weighing oil tank; 5) scales; 6) oil collector; 7) oil flow indicator; 8, 12) three-way valve; 9) reverse valve; 10) filter; 11) valve. A) To the engine; B) from the engine.

In the testing of engines we distinguish between the oil flow rate and the "pumping" of oil. By flow rate we mean the quantity of oil consumed by the engine in one hour of operation. "Pumping" of oil refers to the quantity of oil pumped through the engine in one minute.

The flow rate is governed by the change in weight or volume of oil in the installation tank within a given interval of time. In the case of a volumetric measurement it is necessary to maintain the oil

at an identical temperature at the start and end of the measurement procedure.

The "pumping" measurement is carried out during the course of a single minute, at a steady oil temperature. The quantity of pumped oil is determined from the following formula:

$$Q_{\text{м}} = V_{\text{м}} \gamma_{\text{м}} = V_{\text{м}} [\gamma_{\text{м}\,20^\circ\,\text{c}} - 0,007\,(t'_{\text{м.вых}} - 20)], \qquad (131)$$

where V_m is the volume of pumped oil; $\gamma_{m\,20^\circ C}$ is the specific weight of the oil, at $20^\circ C$; $t_{m.vykh}$ is the oil temperature at the outlet from the structure.

The heat transfer to the oil can be determined from the following expression, on the basis of the "pumping" magnitude:

$$Q_{\text{м}} = c_{\text{м}}\,(t_{\text{м. вых}} - t_{\text{м. вх}})\,Q_{\text{м}}, \qquad (132)$$

where $t_{m.vkh}$ is the oil temperature at the inlet; c_m is the specific heat of the oil.

$$c_{\text{м}} = 0,43 + 0,011 \left(\frac{t_{\text{м.вых}} + t_{\text{м. вх}}}{2} - 15 \right). \qquad (133)$$

The radiators used in the oil system are conventional water-oil tubular radiators. The oil flows through tubes flushed by water or, conversely, between tubes through which water flows. The oil pressure in the radiator must be somewhat higher than the water pressure.

The oil-system tubing diameters must be chosen so that the rate of oil circulation does not exceed 1 m/sec.

All engines undergoing control tests are subjected to internal and external protection. The internal protection of an engine is carried out at the station while the external protection of an engine is handled at the shipping point. Internal protection involves two stages. Upon completion of the control test and prior to the shutting down of the engine, oil is passed into the engine's fuel system rather than fuel (see Fig. 130). The protection of the remaining engine units is

carried out on special carts in the transfer hall to which the engine is directed after the tests.

9. CALCULATION OF THE REQUIRED NUMBER OF TEST STANDS

The number $\underline{n}$ of test stands at a station can be determined from the following formula:

$$n = \frac{\Sigma T}{\Phi} ,$$

(134)

where ΣT is the total gas capacity for the tests, in test-stand hours; Φ is the actual operational time "reserve" for a single test stand, in hours.

The total gas capacity for the tests depends on the production schedule for N engines, the number of test hours, and the time required for auxiliary operations when the engine is on the test stand. This time, regardless of the type of test involved, is composed of the following elements: the time required for the mounting of the engine on the test stand and for the mounting of the engine equipment, the heating and the running-in of the engine, the testing of the engine, the adjustment of the engine, external inspection, adjustment operations (for engines undergoing extensive or special tests), and the time required for the removal of the engine from the test stand.

Let us denote the total time that the engine spends on the test stand during the period of the mounting and testing operations as follows: the delivery time is A; the monitoring time is B; the special-test time is C; prolonged-test time is D; and the repetition-test time is E. The quantities A, B, C, D, and E are determined from the test schedule. The number of engines undergoing special tests is assumed to be equal to $K_1 = 0.025$ N. The number of engines undergoing prolonged testing is denoted by K_2 which is determined from the technical specifications for the test. When taking into consideration the magnitude

of the test-stand load during the course of prolonged tests it is necessary to add 20% to the adjustment operations. The number of engines undergoing repeated tests is assumed to be equal to $K_3 = 0.1 N$. The time of a repetition test is set equal to the time of the delivery and monitoring tests, i.e., $E = A + B$. Consequently, the total annual capacity in hours can be determined from the following formula:

$$\sum T = [1.1(A+B) + 0.025C + 1.2K_3D]N. \qquad (135)$$

The true operational time reserve for a single test stand for a year is less than a calendar year (being a product of the number of working days per year and the possible daily time during which the test stand can be kept in operation) because of time losses due to equipment overhaul, preventive maintenance, and idle time:

$$\Phi = k\Phi_{kal}, \qquad (136)$$

where $\underline{k}$ is a coefficient that is a function of the degree of test-stand complexity, the engine characteristics, and of the degree of equipment wear. It is generally assumed that $k = 0.85-0.95$.

There are 359 working days in a year, and if we assume that the station is in operation on a 24-hour basis, each shift working for a period of 6 hours, $\Phi_{kal} = 359$ work days $\times$ 4 shifts $\times$ 6 hours $= 8616$ hours. In its final form the formula for the determination of the number of test stands can be presented as follows:

$$n = \frac{N[1.1(A+B) + 0.025C + 1.2K_3D]}{k\Phi_{kal}}. \qquad (137)$$

If $\underline{n}$ proves to be a fraction, it must be rounded off to the highest whole number. To achieve the required reserve in station capacity, the recommendations call for the fitting out of a station with $n' = n + 1$ test stands.

10. METHODS OF CONTROLLING NOISE AT TESTING STATIONS

Noise is generated at the testing stations as a result of the suc-
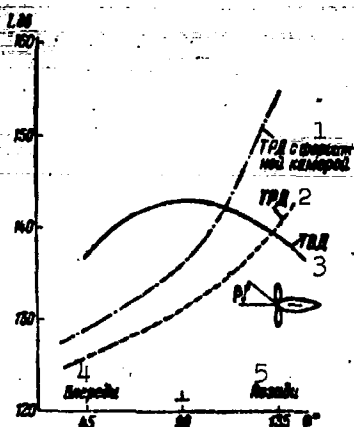
Fig. 133. Total noise intensity as a function of azimuth for various types of engines (of equal thrust) at a distance of 9 m from the source of the noise. 1) TRD [turbojet engine] with afterburner; 2) TRD [turbojet engine]; 3) TVD [turboprop engine]; 4) at the front; 5) at the rear.

tion and particularly as a result of the flow of gas through the exhaust nozzle. In the case of TVD [turboprop-engine] testing, we have the additional noise factor of the propellers.

It should be borne in mind that the exhaust noise produced by air-reaction engines is a high-frequency phenomenon that is particularly dangerous from the standpoint of health. Problems relating to the control of noise at installations for the testing of jet engines are extremely important not only for the servicing personnel at the station and the staff at the plant, but for the population residing in the vicinity of the plant.

Figure 133 shows the data which characterize the change in noise intensity at a distance of 9 m around various types of engines, at approximately identical thrust indices. An increase in the distance to 90 m reduces the intensity of the noise by approximately 20 db.

The decibel is the unit of noise intensity. The number of decibels is determined from the following expression

$$L = 10 \lg \frac{I}{I_0} \text{ db,} \qquad (138)$$

where I is the loudness level of the source; I_0 is the loudness level at the threshold of audibility, equal to 10^{-9} erg/cm$^2 \cdot$sec $= 10^{-16}$ joules/cm$^2 \cdot$sec.

In order to be able to represent the magnitude of the noise produced by jet engines from the physical standpoint and in order to clar-

ify the meaning of the problem under consideration, let us make use of Fig. 134 which shows the physiological effect of varying intensities of noise on a human being. In the case of a loudness level in excess of 80 db it becomes difficult to carry on a conversation; a level of 120 db produces a sensation of pressure in the ear, while at 140 db sound produces pain; at 160 db the organs of hearing suffer mechanical damage. According to the rules of safety, no work should be performed for any prolonged period of time when the noise-level intensity rises above 85 db. Higher sound-pressure values can be withstood for short periods of time.

In the attempt to control noise at testing stations it is absolutely necessary to bear in mind that significant speeds, temperatures, and volumes of exhaust gases complicate the planning, selection of materials, design, and construction of noise-absorption systems.

In this connection, in planning and designing noise-absorbing systems for testing stations it becomes necessary to take into consideration not only the physicomechanical properties of the sound-absorbing materials, but the permissible pressure differences across the gas stream and the available cross sections of the inlet and outlet ducts of the installation. The quantity of secondary air required for the reduction of the gas temperature is determined as part of the design calculation.

In the effort to combat noise it is necessary to take into consideration the possibility of noise propagation in two ways, i.e., through the air and through foundations and the soil. To prevent the propagation of noise through the foundations of the testing installations, the latter are insulated from the ground. Let us dwell in some detail on the methods used to combat noise that is propagated through the air.
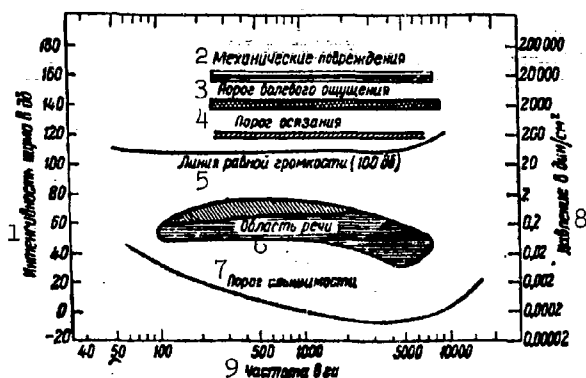
Fig. 134. Physiological effect of noise on hearing organs. 1) Noise intensity, in db; 2) mechanical damage; 3) threshold of sensation of pain; 4) threshold of the sense of touch; 5) line of equal loudness (100 db); 6) speech region; 7) threshold of audibility; 8) pressure, in dyn/cm^2; 9) frequency, in cps.
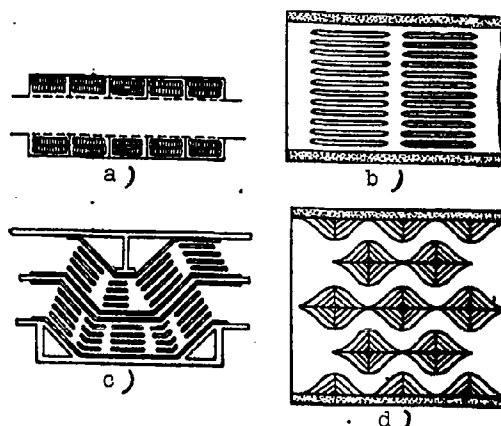
Fig. 135. Diagram of exhaust channels with baffles made of fiber-material panels. a) Channel with panels covered with a perforated steel sheet; b) channel with panels in parallel position; c) channel with turns; d) sinusoidal positioning of panels.

A sound originating at some point of the testing installation begins its propagation in all directions and, on encountering an ob-

stacle, is reflected or partially absorbed. Having been reflected once, the sound may be reflected once again from an obstacle on the opposite side, this procedure continuing to complete attenuation. The better the material of the obstacle absorbs sound, the more rapidly is the sonic energy attenuated. And conversely, good reflecting surfaces, if properly positioned with respect to one another, so amplify a sound that it continues for some time after the generation of the sound from the very source. This phenomenon, known as reverberation, plays a significant role in problems relating to sound treatment. In the presence of significant reverberation, the intensity of auditory reception is markedly increased.

The reverberation magnitude is a function of the degree of sound absorption by wall surfaces and sound-attenuating devices, as well as being a function of the volume of the testing enclosure. It follows from the above that walls, ceilings, and sound-absorbing devices for testing installations must necessarily be constructed of porous materials exhibiting good sound-absorption capacity.

The material used in sound-absorption systems and for purposes of sound treating control rooms at testing stations must:

1) remain rigid if sprayed with fuel, oil, or water, and it must not, in this case, lose its sound-absorbing properties;

2) not lend itself to erosion;

3) be fire-resistant (to reduce exhaust noise);

4) be rigidly mounted to the walls of the test section (during the sound-treatment of the latter).

The majority of these requirements are most completely satisfied by fibrous materials (rock wool, fiberglas, etc.) and porous ceramic and slag-concrete blocks (solid and with hollows).

The least expensive materials well suited for purposes of attenu-

ating noise but incapable of satisfying a number of the imposed requirements can be recommended for use in the inlet systems, i.e., treated wood; for exhaust systems, metal filings or bundles of metal wires. Fibrous materials are used at the installations for purposes of reducing noise exhibiting a wide range of frequencies.

Various configurations (Fig. 135) can be imparted to the sound-absorbing channels. Porous ceramic (solid or hollow) blocks are used to form honeycomb-type channels (Fig. 136). For greater sound-attenuation efficiency, the blocks are shifted at definite intervals by one half of the lateral cross section of the hollows and the duct is frequently fashioned in a staggered [zigzag] array. Ceramics are less efficient in the attenuation of noises in the middle and high frequency ranges, in comparison to fibrous materials. The structural properties of materials used to reduce noise are determined from their strength at various speeds for the gas streams moving past these materials and causing erosion of the material as well as exciting vibrations.

Many fibrous materials are easily eroded and destroyed by great vibrations. In this connection, if the gas stream is moving along a surface at a speed below 25 m/sec the fibrous material is protected by means of a screen or perforated steel sheets (Fig. 137a).
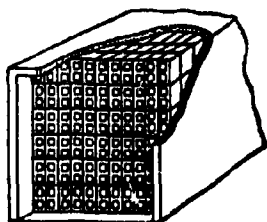
Fig. 136. Honeycomb channel of ceramic blocks hollow from end to end.

At stream velocities below 50 m/sec a layer of strong fabric or a fabric layer covered with a wire screen (Fig. 137b) is inserted between the layer of fibrous material and the perforated outside sheet cover. The fabric must not be very dense so that the acoustic properties of the fill material can be completely exploited.

At gas-stream velocities of 50-140 m/sec an additional protective

- 225 -
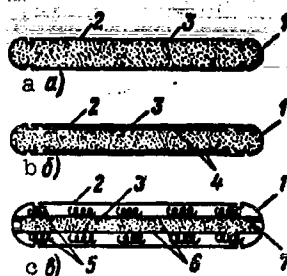
Fig. 137. Design of sound-absorption panels for various gas-stream velocities. a) Up to 25 m/sec; b) below 50 m/sec; c) 50-140 m/sec. 1) Fairings; 2) perforated steel facing; 3) sound-absorption material; 4) glasswool fabric; 5) metal-wire bundle; 6) perforated or cellular barrier; 7) silencer.

facing is used by inserting lighter perforated sheets between the fibrous filler and the perforated outside facing, while the 25-millimeter space between the sheets is filled with bundles of tightly wound steel wire. These bundles do not shrink during operation and provide for high sonic-wave passage (Fig. 137c).

The panels considered in Fig. 137 may be made in the form of vertical barriers or cylindrical structures suspended from special grids in the noise-absorption systems of the testing stations.

The perforated sheet facing of the panels may be destroyed under the action of vibrations as a result of metal fatigue as well as as a result of the loss of plasticity properties on the part of the sheet material (because of a weakening resulting from the holes in the material). To reduce the vibration amplitude of the perforated sheet facing, it must be reinforced with braces.

Figure 138 shows the attenuation curves for sound, in decibels per unit length of channel (30 cm) with respect to frequency octaves for a number of the panels considered above. It is clear from these curves that the most effective noise-absorption system for low (37-300 cps) and middle (300-1200 cps) frequencies is the system in which the panels are distributed sinusoidally. The system with the thickened panels filled with fibrous materials and faced with perforated walls provides for good sound attenuation at low frequencies. The system in which the panels are arrayed in zigzag fashion in the channel (Curve 1)

- 226 -
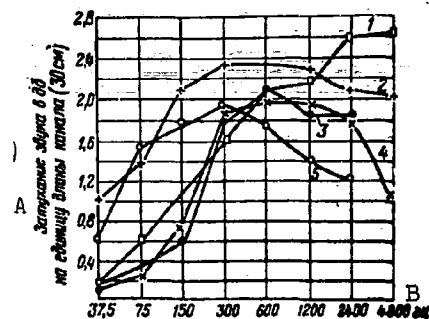
Fig. 138. Attenuation curve per unit length of channel (30 cm) with respect to frequency octaves for various channels. 1) Channel with panels for high flow velocities (see Fig. 135c); 2) channel with sinusoidal panels (Fig. 135d); 3) facing of hollow blocks (Fig. 136); 4) panel baffles 100 mm thick with a distance of 430 mm between the axes; 5) panel baffles 900 mm thick at a distance of 1800 mm between axes (Fig. 135b). A) Attenuation of sound, in db, per unit length of channel (30 cm); B) cps.

provides the best sound attenuation for high frequencies (1200-4600 cps). Thus in order to provide for the most effective attenuation of sound over the entire frequency spectrum, combined sound-absorption systems or sound-absorption systems consisting of combined panels (Fig. 139) should be employed. The inadequacy of the panels considered above is taken into consideration in these panels. The sound-absorption system composed of such elements provides for the attenuation of sound oscillations over the entire range of audible frequencies and because of the high efficiency of such a system it is possible to employ absorption elements of smaller dimensions.

The sound-reducing element consists of a number of curved channels whose walls are made of sound-absorbing materials. The shape of the channels through which the air flows enhances the attenuation of
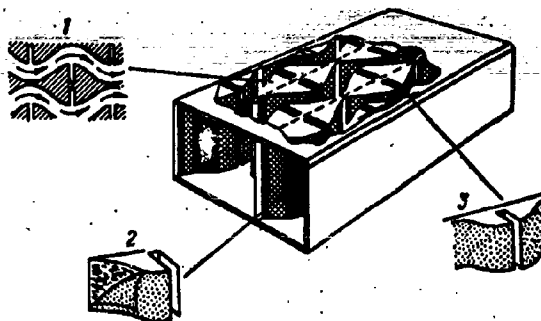
Fig. 139. Diagram of the construction of
an element of a sound-reducing system.
1) Curved channels capable of absorbing
middle-frequency sound; 2) materials ab-
sorbing high-frequency sound; 3) resona-
tors to attenuate low frequencies.
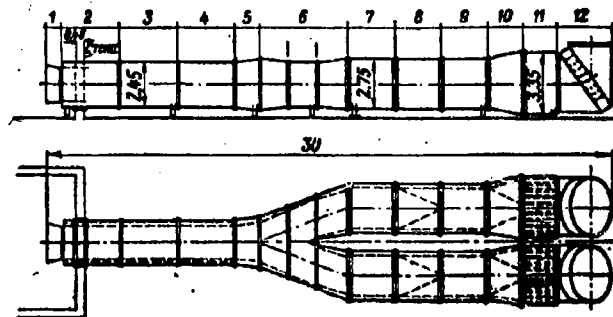
Fig. 140. Double-section silencer. 1) Inlet;
2, 3, 4) Venturi sections; 5) diffuser sec-
tion; 6) branch section; 7) throttling sec-
tion; 8) perforated cone section; 9) section;
10) perforated diffuser section; 11) divider
section; 12) exhaust cascade section.

the middle-frequency sound, while the wall material absorbs the high-

frequency components of the noise. To attenuate low-frequency noise we

use special cutouts known as resonators.

The noise produced by the exhaust gases is significantly reduced

by mixing these with cold air or water. A more efficient and consider-

ably less expensive method calls for the mixing of air with the gases.

An even greater effect is produced by a noise-absorption system that

is based on a combination of the principles of gas expansion and noise absorption. Such a system involves the fact that a stream of exhaust gases carries with it [ejects] a certain quantity of air contained in the test section. The flow of gas that is cooled in this manner enters the diffuser at whose outlet the velocity of the gas flow is reduced, and pressure rises easily, thus making it possible to pass it through a system of slotted channels faced with noise-absorption materials.

Figure 140 shows a structural diagram of a double-section silencer made of steel up to 25 mm thick. An aluminum coating 0.1 mm thick is used to protect the housing of this silencing device against atmospheric influences, and this coating is applied by means of the method of hot pulverization. A layer of aluminum heat-resistant paint is applied over the aluminum coating. The setting up of this silencer unit requires no special equipment. The foundation consists of simple concrete or brick blocks. Where the silencer passes through the wall of the test section special provision is made for packing and sealing that is designed to permit the unit to move back and forth without destroying the structural elements of the building.

The optimum acoustic efficiency of a silencer for various test conditions and at various engine powers can be achieved by controlling a special throttling device carried in the silencing unit. The length of the silencer is approximately 30 m and it weighs about 73 tons.

The cascade ejection of the gases ensures protection against the "reversal" of the hot boxes into the test section at the instant that the engine ceases to operate, thus eliminating any need for valves between the silencer and the test section.

One of the basic means of controlling noise is the sound treatment of the test section. This is achieved by facing the walls, the floor, and the ceiling of the test section with sound-absorbing panels,

similar to those described above.

To control the penetration of noise into the control room of the installation, the doors between the control room and the test section must be of dual construction and they must be covered with sound-absorbing material. The frames and panes of the inspection windows must also be of double construction, or possibly even triple construction (not connected to one another) and, moreover, they must be air-tight. The trenches from the test section to the control room and the openings in the walls between them (for the passage of various manifolds) must be carefully closed off with sound-absorbing materials. The walls separating the test section from the control room must be of double construction, and an air layer is absolutely necessary.
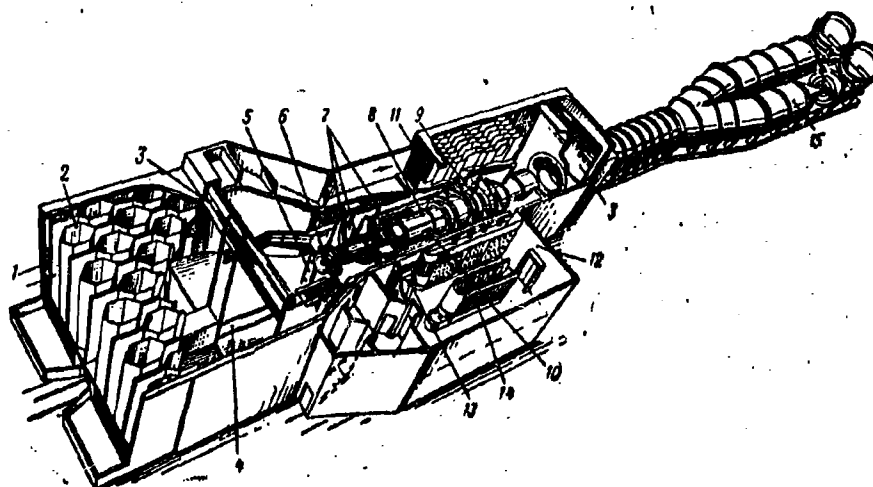
Fig. 141. Installation for the testing of engines, with a silencer. 1) Main air collector; 2) sound-attenuation device; 3) louvers; 4) guide rails; 5) fire-system sprinklers; 6) engine; 7) three-point engine suspension; 8) telescoping section of exhaust tube; 9) demountable section of exhaust tube; 10) observation window in tube; 11) second air collector; 12) control room; 13) inspection window and panel; 14) manometric panel; 15) double silencer.

Let us examine an installation for the testing of engines which is equipped with a silencer (Fig. 141). The sound-reduction systems at

the inlet and exhaust are based on the principles considered above.

The air is taken in through two air collectors, i.e., through the main collector 1 in the forward portion of the station in which the sound-absorbing panels 2 are vertically positioned and form broken-line channels in the in-plan view, and through a second air collector 11 situated at the roof of the testing station to provide the ejector tube with air for purposes of cooling the exhaust gases. A double silencer 15 is positioned at the exhaust.

The above-considered examples of silencing units pertain primarily to stations used for the testing of turbojet engines. In planning stations for tests on TVD [turboprop engines] it is necessary to take into consideration the requirement of air for the propellers and to increase the dimensions of the noise-silencing channels.

11. SAFETY TECHNIQUES DURING TESTS

The technological features of the test process itself call for the implementation of a number of measures to ensure the safety and health of the servicing personnel.

During the tests, and particularly during experimental tests, it is possible for an engine to break apart. In such a case the greatest danger comes primarily from the breaking up of the rotating portions of a compressor and turbine, and in the case of a TVD [turboprop-engine] test or during the test of a ducted-fan engine, there is the danger of the breaking apart of the propeller or fan.

In the case an engine rotor or propeller breaks up, the component parts cause great damage not only to the engine itself, but to the test equipment and installation. In testing practice there have been cases in which a turbine disk rotating at a speed of about 450 m/sec disintegrated. The fragments from the disk penetrated the steel shroud of the turbine and bent the protective steel sheet (20 mm thick)

and penetrated a concrete wall several meters away from the engine to a depth of 150 mm. This example demonstrates the seriousness of the consequences resulting from such an accident.

The inspection window of the control room must be made of bullet-proof glass and must be situated outside of the plane of rotation of the engine's rotor or propeller.

During the course of jet-engine testing it is dangerous to be situated in the vicinity of the airstream entering the engine, or to come too close to the engine exhaust, since this might lead to an accident. Therefore it is strictly forbidden to enter the test section in which an engine is operating, and this applies to all regimes with the exception of the low-gas [idling] regime. The points subject to the action of the exhaust stream from the test section must be fenced off.

Special platforms are set up around the test stand for purposes of fitting out an engine on a test stand prior to a test or to mount the propeller (in the case of a TVD [turboprop-engine] test), thus permitting the servicing personnel to carry out the necessary work.

Of great significance in engine testing installations is the control of the contamination of work areas by fuel vapors, oil, and the products of combustion. For this purpose the air must continuously be purified by means of fresh air-exhaust ventilation.

To avoid the possibility of mercury spillage, the piezometric panels are covered with plastic and special traps are installed at the bottom to contain the spilled mercury. To reduce the liberation of mercury vapors, a small quantity of kerosene or water should be added to the piezometer tubes filled with mercury. The permissible mercury-vapor content in a building or in the surrounding atmosphere calls for no more than 0.01 mg [of mercury] per 1 m^3 of air. Since mercury vapors are extremely harmful, every effort should be made not to employ mer-

- 232 -

cury instruments at the testing installations.

Fuel and oil vapors are dangerous from the standpoint of fire and have a harmful effect on the health of the servicing personnel. Therefore no leakage in the fuel and oil systems of the installation can be permitted. The fuel and oil manifolds are laid down in special channels and they must be connected to the exhaust ventilation system.

The presence of easily flammable materials, open flames, heated engine parts, and hot exhaust gases at a testing station makes it necessary to implement strict measures and fire-safety regulations. Therefore engine testing installations have special facilities at their disposal, in addition to the conventional fire-control devices (fire extinguishers, felting, water, sand, etc.). Thus, for example, a drain manifold intended for the rapid removal of the fuel from the entire system into special tanks dug into the ground are provided for as part of the fuel system. Glass-tube 'evel indicators are not recommended for the fuel tanks or measuring devices.

It is strictly forbidden to smoke, light a match, or to use various fire-producing instruments within the enclosure of the testing station. It is recommended that electric light bulbs in the test sections, control rooms, and production enclosures be mounted in special housings set into the ceiling.

The most effective fire-fighting equipment at the station are the foam and carbon-dioxide devices. In the event of a fire the fire-fighting equipment should be put into operation. Simultaneously, the supply of fuel should be shut off automatically and the drain manifold actuated.

Safety goals impose a number of requirements on the structures of the station. These requirements must be taken into consideration during the planning stage for the station, during the construction of the

- 233 -

buildings, in the width of the passages and the number of exits that will be used in the case it becomes necessary to evacuate all personnel at the station within a period of 3 minutes, and it is also taken into consideration in the lighting for the buildings and the ventilation and heating of the various structures.

Manuscript Page No.	[List of Transliterated Symbols]
187	в = v = vozdukh = air
187	т = t = toplivo = fuel
188	пр = pr = privedennoye = reference
203	д = d = disk = disk
203	н = n = naruzhnyy = external
203	в = v = vnutrenniy = internal
204	ср = sr = srednaya = mean
210	э = e = ekvivalentnaya = equivalent
210	с = s = soplo = nozzle
218	м = m = maslo = oil
218	м.вых = m.vykh = maslo na vykhode = oil at outlet
218	м.вх = m.vkh = maslo na vkhode = oil at inlet
220	кал = kal = kalendarnyy = calendar

Chapter 6

THE TECHNOLOGY OF SERIES TESTING OF AIR-REACTION ENGINES

Testing technology determines the operations and changeovers, and it regulates test sequence, in order to ensure high-quality testing procedures and to make certain that engines are delivered in accordance with the technical requirements imposed.

The technological procedure of testing an engine can be divided into the following stages:

1) the readying of the engine for the test (inspection, mounting of forward connection tubes, various types of sensing elements and devices);

2) the mounting of the engine on the test stand (connection of the measurement, fuel, and oil systems, and the installation of propellers in the case of TVD [turboprop engines]);

3) the actual tests;

4) the removal [dismantling] of the engine from the test stand;

5) the finishing operations on the engine itself after the completion of the test (the removal of the forward connection tubes, the removal of the sensing elements and the various devices, the covering of the holes, partial locking and sealing, and preservation).

The duration and sequence of testing is determined by the type and design of engine and is covered in the test schedule. This chapter proposes to undertake an examination, in the form of an example, of the techniques involved in the testing of turboprop engines with coaxial propellers and some of the features encountered in the techniques

- 235 -

employed to test turbojet and ramjet engines.

1. TECHNIQUES OF TVD [TURBOPROP-ENGINE] SERIES TESTING

The procedure involved in the series TVD testing under considera-
tion here consists of two stages.

The first stage: a turboprop engine with two coaxial propellers
is tested on a rigidly fixed test stand (see Fig. 117), the effective
power and reaction thrust not being measured.

The second stage: a turboprop engine is tested on a combined test
stand, without propellers (see Fig. 128), the power at the shaft of
the reduction gear and the thrust developed by the exhaust nozzle be-
ing measured simultaneously.

Preparation for testing

The condition of the equipment and instruments of the testing in-
stallation is of great significance for the successful completion of
engine tests, and any irregularities on the part of this equipment or
the instruments may result either in distortion of the test results or
in serious damage to the test stand.

The test stand and its equipment, and the systems and instruments
of the testing installation are regularly checked and subjected to pre-
ventive maintenance and regular check operations. The monthly preven-
tive-maintenance operations involve the thorough cleaning and inspec-
tion of the test stand, the engine-servicing platforms, the oil and
fuel systems, the oil and fuel filters, the samplers, scales, etc.

The filters of the oil and fuel systems of the installation are
inspected and flushed with gasoline and the inspection results, inso-
far as these pertain to the filters, are recorded in maintenance logs.
The fuel, oil, and similar hydraulic systems are checked for leaks.
The action of the gas-control lever on the panel is checked for smooth-
ness of operation. Seizing of the engine control system and labored

operation are intolerable.

. Particular attention is devoted during the preventive-maintenance operations to the checking out of the instruments; they are removed from the panel and sent to the instrument division of the station for checking.

The electric power supply for automatic starting is checked by operating the appropriate toggle switches and monitoring the signal lights. The devices and cables used to raise the engine — the electric overhead cranes — are inspected and they are checked in operation.

Before the tests are begun, the required documentation is prepared, i.e., the testing schedule, the forms for the various stages of the test, the technical specifications, and the instrument approval blanks.

Delivery, transportation, and installation of engine

The assembled engine is delivered to testing-station workers at the transfer point. On delivery the engine is inspected superficially, a check is made to see whether there are cover plates over the compressor inlet, the exhaust nozzle, the connection tubes for the test-stand systems, and an inspection is also carried out to make certain that the seals on the control screws for the various units have not been broken. When the engine is passed from the assembly shop to the testing station, all of the technical documentation (the technical specifications and approval blanks) must be submitted together with the engine itself.

Once in the testing section, the engine is raised from the transportation carrier by means of an electric overhead crane and it is placed on the engine frame of the test stand, where it is fastened and positioned in place. Then the hoses and tubing of the fuel and oil systems and engine-control connecting rods are attached. The sensing ele-

- 237 -

ments for the measurement of temperature and vibrations are then attached, as are the hoses and tubing for pressure measurements, etc.
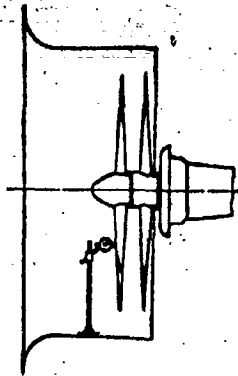
Fig. 142. Verification of propeller-blade beat.

When TVD [turboprop engines] are being tested on a rigidly fixed test stand, the propellers are mounted at the same time that the plumbing and electric wiring to the engine shaft are connected. The blades and hubs of the propellers are carried separately and assembled at the test section.

The final operation in the installation of the propellers is the checking of blade beat. An indicator is mounted on a special base for this purpose and its arm is moved into position to come into contact with the blades of the forward propeller at a certain diameter (the point at which beat is checked is indicated by means of a line on all of the propellers).

As the propeller turns the deflections of the indicator arrow for each of the blades is manually recorded. An indicator setup for checking of beat is shown in Fig. 142. The highest deflection difference must not exceed the permissible values stipulated in the operational instructions for the propeller (1.0-5.0 mm). This operation is subsequently repeated for the second propeller.

The presence of significant beat indicates improper mounting of the blades in the hub or that the propeller has not been seated properly on the shaft of the engine, resulting in dynamic imbalance of the propeller and engine vibrations.

The existence of a powerful airstream in the test section during the course of the test calls for the reliable attachment of the hoses, tubing, and electric wiring that is connected to the engine.

Upon completion of the installation phase, the engine is readied for start; for this purpose the oil pressure in the test-stand manifold is checked, as is the functioning of the sampler adjustment control, and the quantity of oil in the oil tank. A careful check is made to see that no extraneous items have been left in or around the engine, the test section, or the servicing platform. Tools, devices, covering plates, and similar items are removed from the test section.

If all of the preliminary operations have been completed and if the readiness of the installation has been verified, the engine is started directly.

Delivery test

The delivery test is begun with a false start of the engine by turning it over by means of the starter, but without igniting the fuel. This false start is carried out in order to fill the oil system of the engine with oil, to check the operation of the starter, the drain system of the combustion chamber, and to ready the fuel system.

The oil in the oil system of the installation must be heated to 40-50°C before the start. It is particularly necessary to heat the oil during the winter when, given low ambient-air temperatures, the viscosity of the oil is increased.

The engine is started by depressing a starter button on the control panel, all of the remaining operations being carried out automatically until entry into the low-gas regime. The engine functions for a period of 5-10 minutes in the low-gas regime, after which it is stopped by means of a shutoff valve. The following measurements are taken during the starting procedure and the low-gas operation:

1) the operating time of the starter;

2) the time required for the engine to enter the low-gas regime from the instant of start; .

- 239 -

3) the number of engine revolutions;

4) oil pressure;

5) fuel flow rate;

6) the temperature of the gases behind the turbine;

7) the temperature of the oil at the inlet to and the outlet from the engine.

When the engine is stopped, a determination is made of the ease with which the engine makes the transition from 1000 rpm to complete stoppage (with respect to the time of stoppage). This parameter indicates the ease with which the engine rotor can rotate and it also points to the absence of extraneous friction in the component parts and units.

It is advisable during the course of the delivery tests to combine the running-in of the engine and the adjustment of the fundamental parameters. Thus, for example, during the running-in phase the operation of the propeller feathering system should be checked. The running-in of the engine component parts is carried out in several stages, with gradual increase in power.

The first stage involves the rpm adjustments, raising the number of revolutions to their maximum. The blades of the propellers are, in this case, set for fine pitch (an unloaded propeller). The revolutions are raised stepwise through 200-500 rpm; the staytime at each number of revolutions amounts to 5-10 minutes during which time the basic engine parameters are measured and the functioning of the units is checked out.

The second stage involves the adjustment of the engine with respect to power, with gradual stepwise increases in the latter to a regime that is 0.7 of the rated regime.

The third stage involves the adjustment of the engine with respect

to power to the takeoff regime.

The engine operating regime in the case of delivery tests is governed by the fuel flow rate. For each power stage the engine is in operation for a period of 5-15 minutes during which all parameters are measured.

When the engine is stopped between the various running-in stages, adjustment and superficial inspection operations are carried out.

During the running-in procedure the functioning of the auxiliary units — the electric generators, regulators, servodrives, hydraulic pumps, air compressors — are checked out; in addition, a check is carried out on the operation of the sensing elements and the automatic units of the control system, any required adjustments being carried out at this time. A sudden (within 1-1.5 sec) movement of the throttle lever from the low-gas stop to the maximum rpm stop is carried out to test engine pickup, while the return of the throttle lever is used to check on the reduction in the fuel flow rate.

The results of engine adjustments are verified at the end of the delivery testing procedure for all regimes from low-gas to takeoff. Upon completion of the delivery tests all control units are covered and sealed.

An engine's fuel system is preserved by filling it with liquid oil by turning it over or through the false-start procedure. All operations carried out with the engine as part of the delivery tests are recorded in a log.

Some defects resulting from poor engine assembly (oil and fuel leakage at manifold joints) are eliminated by assembly-shop personnel during the course of the tests. An engine which has passed the delivery tests is taken down from the test stand and sent for complete overhaul to the assembly shop. If the overhaul and inspection of the component

parts reveals no deviations from the technical requirements, the engine is reassembled and sent on for a control test involving the use of a hydraulic brake.

Control tests on a hydraulic-brake test stand

The control test of an engine on a test stand with a hydraulic brake consists in:

1) the readying of the test stand for the test;

2) the mounting of the engine on the test stand;
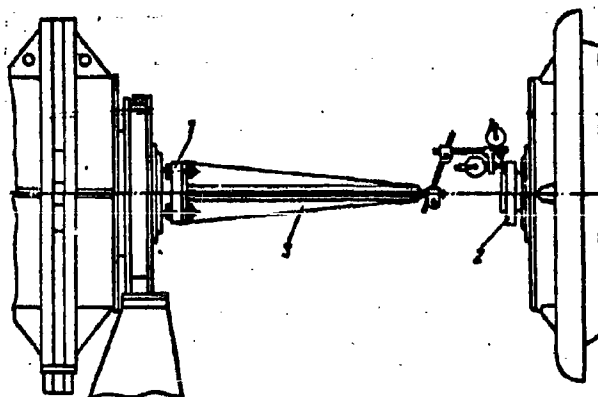
Fig. 143. Device for the centering of the engine and the hydraulic brake. 1) Hydraulic-brake shaft; 2) engine shaft; 3) centering device.

3) the starting and running-in of the engine;

4) the measurements at the control points;

5) removing the engine from the test stand.

For the purposes of the test the engine is assembled in the assembly shop without a reduction gear but with a shaft for the direct connection of the engine rotor to the hydraulic brake. It is not impossible in this case to test an engine with a reduction gear on the hydraulic-brake test stand. For this purpose the test stand must be equipped with low-rpm hydraulic brakes of corresponding power. The dimensions of low-rpm hydraulic brakes are great and may screen out the

air inlet to the compressor. It is for this reason that the units without reduction gears have gained the greatest acceptance for the testing of TVD [turboprop engines].

In readying the hydraulic-brake test stand for the tests it is inspected and the positions of the levers for the systems used to measure torque and exhaust-nozzle thrust are checked out, as is the reliability of the fuel- and oil-system valves, the ease of engine- and hydraulic brake-control system operation, the condition of the lift devices, the availability of the necessary tools, and the hoses, manifolds, and electric wiring conduits are checked for cleanliness and to make certain that they are whole.

The testing equipment, fuel- and oil-analysis data sheets, and the inspection forms and technical-data sheets for the monitoring-measuring instruments must be readied prior to the start of the tests.

All of the instruments must be checked out by the plant laboratory at the intervals established by the requirements of the test-adjustment operations.

The engine assembled for purposes of hydraulic-brake testing is mounted on the test stand and held in the supports of the engine frame, thus making it possible to move the engine in order to line it up [make it coaxial] with the rotor of the hydraulic brake. The shafts of the engine and the hydraulic brake are connected by means of a special shaft fitted out with splined couplings which allow for but little misalignment of the engine and brake axes.

The shaft of the engine is centered with respect to the shaft of the hydraulic brake before the introduction of the connecting shaft. As the shaft of the hydraulic brake is turned, the indicators mounted on a special rod fastened to the flange of the brake shaft come into contact (with their extensions) with the flange of the engine shaft.

- 243 -

In four positions separated by 90° around a circle, the deviations of the indicator arrows are recorded. By means of the movable supports of the engine frame, the engine is shifted so that the indicator deviations fall within the permissible limits in both the radial and the axial directions. In the radial direction beats of ±0.1 mm are regarded as permissible, while in the axial direction ±0.05 mm is acceptable. The indicator installation used to check centering is shown in Fig. 143.

The fuel and oil systems, as well as the pressure and temperature measuring sensors, are installed and connected at the same time that the engine is being centered.

In readying the engine for start it is necessary to confirm that there is oil in the oil tank, and when M_{kr} and R_s are being measured by means of hydraulic dynamometers it is necessary to make certain that there is oil in the measurement system. The fuel pressure in the test-stand manifold must be checked, and the test section and the engine inlet must be inspected to make certain that no extraneous items have been left behind.

In testing an engine on the hydraulic-brake installation it is necessary to undertake a careful check of the manner in which all of the tubing and wiring to the hydraulic brake has been attached in order to avoid the entry of any extraneous items into the compressor, since this would result in the destruction of the engine. Under winter conditions the appearance of water at the inlet to the engine, because the water system was not properly sealed, may result in the formation of ice on the compressor blades, which will damage them.

The ease of engine rotor rotation is tested by manually turning the rotor through several revolutions. After the withdrawal of the servicing personnel from the test section, the fuel and oil valves are opened, the automatic starter toggle switch is actuated, and the pumps

for the torque and thrust measuring systems are put into operation.

An engine on a hydraulic-brake installation can be started both by means of a starter as well as by means of an outside electric motor with smooth revolution control. In the first case the starting is an automatic procedure controlled from the control panel by depressing a starter button until the engine enters the low-gas regime; in the second case, the engine is started by having the electric motor turn over the engine, i.e., the operator shifts the throttle lever manually to provide the fuel and start the ignition.

The running in of the engine with respect to revolutions is carried out by changing the number of revolutions stepwise from the low-gas regime to n_{max}. The operating time at each number of revolutions is 5-10 minutes, during which the engine parameters are measured.

Upon completion of the running-in procedure an external inspection of the engine is carried out, and this pertains as well to the units of the engine and the hydraulic brake; in addition, the oil filters of the test stand are checked.

Before measurement of the control points, the calibration of the torquemeters and the thrust-measuring units is checked. The control points are determined for regimes identical to engine-operating regimes in which the engine was tested together with its propellers. During the course of the control-point measurement the resistance moment developed by the hydraulic brake is changed by increasing or reducing the supply of water. The parameters are generally established at the completion of operations in a particular regime on the basis of time. The measured parameters are evaluated and the characteristics are constructed from the derived data. After the evaluation of the test results the fuel system of the engine is treated for storage and the engine is dismantled and removed from the test stand. A reduction gear

and various units are mounted on the engine that has passed control tests with the hydraulic brake and this is done in the assembly shop; subsequent to this the engine is sent for control testing with propellers.

A torquemeter (IKM) for the determination of power is frequently mounted in the reduction gear of a turboprop engine. Given sufficient accuracy and operational stability for the IKM, the control testing of a series-produced engine on a hydraulic-brake test stand can be bypassed or it can be carried out on a selective basis, spotchecking individual engines. In this case, the test cycle for the turboprop engine is radically reduced, the procedures are simplified, and the costs involved in testing are reduced. In the case of complete rejection of hydraulic-brake tests, there is no need to equip the testing stations with complex hydraulic-brake installations.

Control testing with propellers

Control testing with propellers involves checking the quality of the final assembly and adjustments, completing the delivery paperwork for the representative of the client, and the preparation of the engine for storage. The engine is mounted on the test stand in the sequence indicated earlier.

During the control tests the basic engine parameters are carefully checked, as is the operation of the engine in all operational regimes; the starting of the engine, its pickup and fuel-feed reduction are also checked, and so is the functioning of the automatic propellor feathering system, and the functioning of the de-icing system.

Prior to each engine start by means of a starter, the ease of rotor rotation by the turning of the latter through several propeller revolutions is checked. The time required for the engine to stop when the fuel supply is cut off at n = 1000 rpm is measured for the charac-

teristic of the state of the engine rotor.

In case individual engine parameters deviate from the technical specifications, they can be regulated and tested once again.

After a check on the quality of the assembly and the adjustment procedures, all fuel- and oil-system filters of the engine are inspected and flushed clean. Then all of the devices on the control-system units are closed and sealed, subsequent to which the engine is turned over for the preparation of the delivery documentation to the representative of the client. During this phase it is recorded in the test log that the engine has been adjusted in accordance with testing procedures and that all the engine parameters correspond to the technical requirements.

The delivery documentation confirms that the engine has been subjected to a final and detailed check of operation at all operational regimes, the parameters having been measured in the presence of and with the participation of a representative of the client. Deviations in the parameters from the technical requirements and the existence of defects cannot be permitted at the time the engine is delivered.

Upon completion of the delivery tests, the engine is subjected to an external inspection, and the fuel and oil filters are all checked and flushed clean. The data derived during the course of the tests are evaluated and the required graphs are plotted. The basic engine data derived during the control tests are entered on the engine-specification blanks.

The engine that has passed through the control test is then treated for storage. The detailed sequence for the internal and external treatment of the engine for storage and packing is taken from a special manual.

The testing log

A testing log is maintained throughout the course of the delivery and control tests of the engine. Prior to the initial start of the engine the testing log must indicate:

1) the number of the engine, and that of its units and the propeller;

2) the date and time at which the engine arrived at the installation;

3) the number of the testing installations;

4) the type of test (delivery, control on the hydraulic-brake installation, control with propeller);

5) the results of the analysis of the oil and fuel in the systems of the installation (specific weight, viscosity, flash point, absence of mechanical impurities and water);

6) the hours and minutes the engine had been in operation in previous tests, if such had been carried out;

7) the readiness of the engine for start.

During the course of the tests, in addition to measuring the engine parameters for the various regimes, all work with the engine is recorded (elimination of defects, replacement and adjustment of units). If the engine ceases to function at a time not specified in the testing schedule, a detailed record of the factors responsible for this stoppage is included in the log, as well as a listing of all subsequent operations performed with the engine. If the test is interrupted for some reason and the engine is removed from the test stand, this is also indicated in the log.

The testing logs represent a part of the basic documentation and they must therefore be kept with extreme care.

Evaluation of results

. The parameters that are measured during the course of engine test-
ing must be referred to standard atmospheric conditions. Reference to
the MSA [International Standard Atmosphere] makes it possible to com-
pare series-produced engines with one another under the conditions of
their tests for various atmospheric conditions (winter and summer,
night and day, etc.).

In evaluating the test results for a TVD [turboprop engine], un-
like the generally accepted reference parameters for a TRD [turbojet
engine], we introduce the concept of normal reference parameters, i.e.,
$N_{e\ norm}$, $G_{t.norm}$, $C_{N\ norm}$, $R_{s.norm}$, etc.

The word normal refers to the values of the parameters of the en-
gine being tested, these values referred to standard atmospheric con-
ditions and derived with the control units in identical positions.

The normal reference parameters are used only in the procedure
for the evaluation of test results for TVD [turboprop engines]. The
reference coefficients derived on the basis of experimental tests are
suitable only for a given TVD design with a definite and constant law
governing the control of revolutions and fuel flow rate. The values of
the normal parameters are given in the technical specifications.

The engine operating regimes during the determination of the con-
trol points on a hydraulic-brake test stand are determined from the
load and the revolutions. The fuel flow rate and similar engine param-
eters are defined as functions of the regime. The loads applied to the
brake are calculated.

In tests of engines together with their propellers, the regimes
are determined by the fuel flow rate, while the power at the engine
shaft and the reaction thrust are determined by calculation on the
basis of data derived from the test of the engine on a hydraulic-brake

- 249 -

test stand. Both in the case of a test conducted on a hydraulic-brake test stand and when the tests are conducted with propellers the agreement between the engine data and the technical specifications must be determined under identical operating conditions for the engine.

The loads for the regimes in which the engine is tested on a hydraulic-brake test stand are calculated in the following order. The equivalent power of a turboprop engine is determined from Formula (130). In a test of an engine on a test stand with a hydraulic brake, the normal value of the power $N_{e \ norm}$ along the engine shaft is taken as the basis for the calculation of the loads for the assignment of regimes, and the magnitude of this power for each regime is found from the following formula

$$N_{e \text{ норм}} = m N_{\text{э. норм}},\qquad (139)$$

where

$$m = 1 - \frac{0,91 R_{c. \text{ норм}}}{N_{\text{э. норм}}}.\qquad (140)$$

The magnitude $N_{e \ norm}$ is given in the technical specifications. The values of the coefficient $\underline{m}$ for testing under ground conditions are calculated according to the characteristics determined during the process of the experimental tests conducted on the engine. Since the tests generally proceed under conditions other than standard atmospheric conditions, the magnitude of the load of the hydraulic brake must be selected so that after reference to MSA [International Standard Atmosphere] the power of the engine is equal to $N_{e \ norm}$.

Under the given atmospheric conditions the magnitude of $N_{e \ zam}$ for each regime is determined from the following formula:

$$N_{e \text{ зам}} = K_N N_{e \text{ норм}},\qquad (141)$$

where K_N is the reference coefficient that is a function of the pressure and temperature of the outside air, and by means of which coeffi-

cient we take into consideration the law governing engine control with respect to revolutions and fuel flow rate. The value of the coefficient K_N is determined from curves constructed on the basis of experimental tests conducted on the given type of engine.

At a given power the engine is loaded with the hydraulic brake that develops the corresponding braking moment on the engine shaft. In this case the given operational revolutions of the engine are maintained at a constant value by the rpm regulator which automatically increases the supply of fuel with an increase in the braking moment.

The braking moment of the hydraulic brake is equal to the torque of the engine and it is measured in the form of the force P on arm l. The magnitude of the load (the force P) for the assignment of the engine regime with respect to the measured power is determined from the following formulas

$$N_{e\,зам} = \frac{M_{кр}n}{716,2} = \frac{.Pln}{716,2},$$

whence

$$P = \frac{716,2N_{e\,зам}}{ln} = \frac{716,2K_N}{l}\frac{N_{e\,норм}}{n}. \qquad (142)$$

The calibration graph showing the pressure on the torquemeter of the hydraulic brake as a function of the load on the hydraulic-brake lever is used to determine the required engine operating regime.

Calculation of normal TVD [turboprop engine] parameters for the case of hydraulic-brake testing

To determine the agreement between the basic engine data measured on a test stand with a hydraulic brake and the data called for in the technical requirements, it is necessary to refer the values of the measured parameters in the case of constant control-unit positions to the normal atmospheric conditions. During the course of testing TVD [turboprop engines] we measure and calculate the following quantities:

N_e, $\bar{R}_s$, G_t, and T^*_4 (the stagnation temperature of the gas stream be-
hind the turbine). The normal values of the parameters are calculated
on the basis of the following formulas:

$$N_{e\,норм} = \frac{N_{e\,зам}}{K_N}; \qquad (143)$$

$$G_{т\,норм} = \frac{G_{т\,зам}}{K_G}; \qquad (144)$$

$$R_{с.\,норм} = \frac{R_{с.\,зам}}{K_R}; \qquad (145)$$

$$T^*_{4\,норм} = \frac{T^*_{4\,зам}}{K_T}; \qquad (146)$$

$$C_{N\,норм} = \frac{G_{т.\,норм}}{N_{е.\,норм}}, \qquad (147)$$

where K_N, K_G, K_R, and K_T are the respective reference coefficients.

The normal parameters of an engine in the case of control tests
with propellers are also calculated from these formulas. The number of
engine revolutions both in the case of tests on a test stand with a
hydraulic brake and in the case of propellers remains constant and
equal to n_{norm}.

In the event that n_{zam} deviates from the given value of the number
of revolutions, corrections are introduced into the calculation of
$N_{e\ norm}$ and $R_{s\ norm}$. The magnitude of these corrections is determined
from curves constructed on the basis of experimental tests.

2. FEATURES OF PROLONGED TESTING

Prolonged tests are carried out in individual stages. The dura-
tion of the continuous-operation stage is governed by the purpose for
which the engine is intended. After each stage of a prolonged test the
engine is inspected and certain adjustments are made.

The total number of stages in a prolonged test is governed by the
duration of the individual stages and the established service life.
The testing regimes and operation of an engine for a particular stage
are set so that after the completion of a prolonged test the operation

of the engine in the various regimes corresponds to the announced data. Thus, for example, during the course of a 100-hour test, 40 hours must be in the nominal [rated] regime, 10 hours must be under takeoff conditions, and 50 hours must involve engine operation in cruising regimes. The sequence of the regimes in the stage correspond approximately to the possible sequence of regimes in actual operation.

Prior to and after prolonged tests the basic characteristics of an engine are determined in order to define the stability of the engine parameters over a long period of operation. The change in the basic parameters of an engine during the course of a prolonged test is determined on the basis of data derived during the tests. The mean power values, and the mean values of reaction thrust and specific fuel consumption, as well as of other parameters, are calculated during the various stages of prolonged testing with respect to the averaged hourly fuel flow rate for the given regime. The derived data are compiled into a table.

In compiling the reports on the conduct of prolonged testing, in addition to the tables of the mean parameters and the graphs indicating changes in these parameters during the course of the test, a report is also made of the defects recorded during the course of the test, with a detailed description of the nature of the defect and its causes. The report also includes photographs of individual defective component parts and a note is made as to the conclusions drawn from the results of the prolonged test; finally, recommendations are made with respect to the elimination of the discovered deficiencies.

In the event of an unsatisfactory conclusion to a test (the destruction of component parts or units during the course of the test or significant wear and damage discovered during the overhauling of the engine) the factory must determine the factors responsible for these

- 253 -

defects and to develop and implement measures to eliminate them. Subsequently, the test must be repeated. If even a single engine from a given batch fails to pass the test, the entire batch must be rejected. These engines may subsequently be accepted, if after the implementation of the aforementioned measures the first engine from the batch successfully passes the series-production prolonged testing procedure.

3. FEATURES ENCOUNTERED IN THE TESTING OF TRD [TURBOJET ENGINES]

A turbojet engine, unlike a turboprop engine, is not fitted out with a high-stress reduction gear and a propeller. The turbojet engine requires no prolonged running in of the component parts, since the engine rotor turns in antifriction bearings and there are no reduction gears that require careful running in. The testing procedure is further simplified by the fact that there is no need to measure engine power. The time required for the testing of a TRD [turbojet engine] is considerably less than that required for the testing of a TVD [turboprop engine].

The thrust of a turbojet engine is a strong function of the number of revolutions and high accuracy in the measurement of this number of revolutions is therefore required. In TRD testing it is extremely important that the temperature field behind the turbine be adjusted. The field is evaluated in terms of the mean temperature and its uniformity throughout the entire field. The reaction-thrust adjustment for the engine is achieved by choosing a nozzle of the required cross section. A reduction in nozzle cross section increases reaction thrust, and vice versa.

On the whole, the technological process of the delivery, control, and prolonged tests of turbojet engines is quite similar to the techniques employed in testing turboprop engines. The preparatory work, assembly, preventive-maintenance operations on test-stand equipment,

- 254 -

and the evaluation of the TRD test results have much in common with similar procedures involved in the testing of TVD and they will therefore not be examined here.

The referral of the measured TRD parameters to the MSA [International Standard Atmosphere] is carried out with the following formulas: engine thrust

$$R_{np} = R_{вам} \frac{760}{p_{вам}},$$ (148)

engine revolutions

$$n_{np} = n_{вам} \sqrt{\frac{288}{T_{вам}}},$$ (149)

hourly fuel flow rate

$$G_{np} = G_{вам} \frac{760}{p_{вам}} \sqrt{\frac{288}{T_{вам}}},$$ (150)

specific fuel consumption

$$C_{R\,np} = C_{R\,вам} \sqrt{\frac{288}{T_{вам}}},$$ (151)

gas temperature behind the turbine

$$T_{4\,np}^* = T_{4\,вам}^* \frac{288}{T_{вам}}.$$ (152)

4. GENERAL DATA ON PVRD [RAMJET] TESTS

The purpose of testing ramjet engines includes:

1) verifying the quality of engine assembly;

2) checking the correspondence between the actual and the required thrust characteristics;

3) a study of engine cycle stability in various regimes and determination of flame separation and overheating of individual component parts of the hot section;

4) verifying the operational reliability and stability of the fuel-supply regulator;

5) checking the reliability of engine start under various condi-

- 255 -

tions with respect to the M(ach) number and the air temperature at the inlet.

For purposes of operating a PVRD [ramjet] under static conditions it is necessary to develop air ram pressure at the inlet to the engine.

The air is supplied to the PVRD by means of a special device making it possible to change the speed and temperature of the air. The rate of air supply is a function of the engine testing regimes. A diagram of the simplest installation for the testing of a subsonic ramjet engine is shown in Fig. 144. The engine is mounted on a test stand consisting of a frame mounted on flexible supports and fitted out with levers that transmit the force of the thrust from the PVRD to a dynamometer.
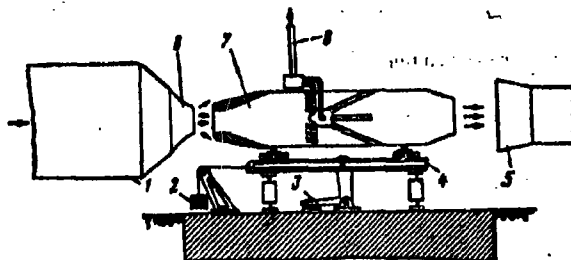
Fig. 144. Diagram of PVRD testing installation. 1) Compressed air receiver; 2) calibration device; 3) thrust measuring unit; 4) testing stand; 5) exhaust tube; 6) fuel supply; 7) PVRD [ramjet]; 8) nozzle.

In order to avoid distortions of the velocity field at the inlet diffuser, the engine axis must coincide with the axis of the air-supply connection tube. Fuel is supplied to the engine from a flow tank by means of the test-stand pump which ensures the technically required flow rates and pressures. The fuel pressure at the inlet to the engine is controlled from the control panel by means of a throttle valve.

A necessary condition for PVRD testing is the verification of

starting reliability, since an engine mounted in a rocket or an air-craft cannot be started independently and must be capable of reliable start in the air at comparatively great flight velocities.

One of the important features encountered in the testing of PVRD [ramjet engines] is the short duration of these tests (of the order of 2-4 minutes); therefore, the measurement of the engine parameters and their exact determination must be carried out automatically. Generally, the instruments that measure these parameters are mounted on an individual panel and these instruments are then photographed at definite intervals of time for each operating regime.

The preventive-maintenance operations carried out on the installation are analogous to those described above. Particular attention is devoted to the servicing of the complex air supply system and its care and maintenance.

Prior to each test of an engine the thrust-measuring units are calibrated. A necessary condition of the preparatory operations is the verification of the airtight sealing of the tubes and hoses of the air-duct parameter measuring systems. The presence of even insignificant air losses will result in substantial distortion of the results.

In testing PVRD on the installation whose diagram is shown in Fig. 144, we find that the thrust that is measured is lower than the theoretical by the quantity R_{sopr} which represents the external drag that has not been taken into consideration here:

$$R = R_{изм} + R_{сопр}.$$

(153)

The magnitude of the force of the external drag R_{sopr} is a function of the parameters of the approaching stream. This force is determined from data derived in cold wind-tunnel tests of the engine and these data are used to construct curves indicating the relationship between R_{sopr} and the velocity of the approaching stream.

- 257 -

Unlike TVD and TRD, this type of engine requires no delivery tests for purposes of adjustment and running in; therefore, in series production of PVRD, these engines are subjected only to control tests. In addition to the control tests, individual engines are randomly subjected to prolonged test procedures involving the total service life.

Manuscript Page No.	[List of Transliterated Symbols]
250	э = e = ekvivalentnaya = equivalent
250	c = s = soplo = nozzle
250	норм = norm = normal'noye = normal
250	зам = zam = zamerennaya = measured
251	кр = kr = krutyashchiy = torque
255	пр = pr = privedeniye = reference
257	сопр = sopr = soprotivleniye = drag

Chapter 7

ENGINE FLIGHT TESTS

The flight-engineering characteristics of aircraft are determined in great measure by the characteristics and the operational indices of their engines. There are always some differences between the actual flight characteristics of an engine and those derived at the stations or under conditions encountered in high-altitude installations. Moreover, it is important to clarify the features of the operational flight characteristics of a particular type of engine and its shortcomings, as well as to determine the means by which these defects can be eliminated. These conditions and requirements govern the need for the execution of flight tests for all newly designed engines and their modifications.

Each type of flying craft is given a definite designation and for this reason the engines that it carries must exhibit the required operational characteristics for the conditions under which it is to operate. In this connection, the scope, the purpose, and the methods of the flight tests vary as a function of the type of engine and the designation of the aircraft.

When a single engine is mounted on various aircraft, its operation must be checked for each type of aircraft. The need for this type of test is brought about by the fact that aircraft of various designations are used under nonidentical flight conditions and there are also, as a rule, a variety of structural configurations of the powerplants, including the inlet channels and the gas-exhaust tubes, all of which

serve to exert considerable influence on engine operation.

Higher requirements with respect to the accuracy of the measured parameters are imposed on flight tests. Since a flight experiment is very expensive, it is desirable to reduce the testing time to the minimum without impairing the quality of the test. The majority of the measured parameters are recorded by special automatic recording units.

The present chapter presents only the most general of information on engine flight tests.

1. AIRCRAFT FOR FLIGHT TESTS

Flight tests of VRD [air-reaction engines] are carried out either directly on the aircraft for which it was designed, or these tests are conducted on special aircraft known as flying laboratories.

The primary flight tests of a newly designed engine are, in many cases, associated with great difficulties and risk when conducted on an experimental aircraft.

The flight tests of an engine are significantly simplified through the use of special flying laboratories that are modifications of series-produced aircraft. The experimental engine is mounted in the fuselage of the flying laboratory or suspended in a special pod beneath the wing or the fuselage. Sometimes the experimental engine is mounted above the fuselage or in the aircraft's tail assembly. The assembly of all of the elements of the powerplant on the flying laboratory must approximate the assembly of the powerplant of the experimental aircraft for which the engine being tested was designed to the greatest possible extent. This makes it possible to undertake a detailed study and adjustment of the various units and individual systems of the experimental aircraft's powerplant simultaneously with the flight tests of the experimental engine.

Figure 145 shows an over-all view of a flying laboratory modified

from a series-produced aircraft for the testing of small air-reaction engines. The experimental engine is suspended on a pylon beneath the right wing of the aircraft. A fuel tank is mounted beneath the left wing, this tank exhibiting the same configuration as the powerplant of the experimental aircraft.
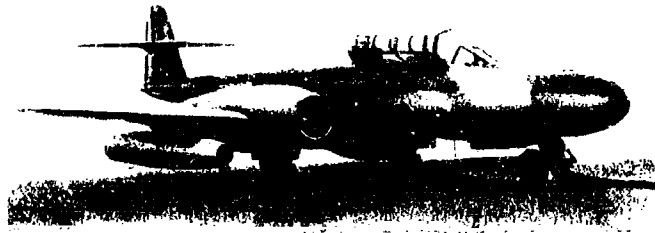
Fig. 145. Flying laboratory.

Figure 146 shows a diagram of the mounting of a ramjet engine on an aircraft for subsonic flight tests. The engine is positioned over the fuselage of the aircraft in such a manner that the engine's axis is parallel to the longitudinal axis of the aircraft. When the engine being tested is suspended beneath the fuselage provision is made for complete or partial withdrawal of the engine into the cargo compartment of the fuselage during taxiing, takeoffs, and aircraft landings. Moreover, devices are included in the flying laboratory to make possible the dumping of the experimental engine in the case of an emergency. The powerplant of the aircraft is fitted out with a special fire-extinguishing system.

In converting a series-production aircraft into a flying laboratory, all equipment not needed for the flight tests is removed from the aircraft. This reduces the weight of the aircraft and makes it possible to provide conditions that make the work of the crew easier and provides the space needed to carry the experimental equipment.
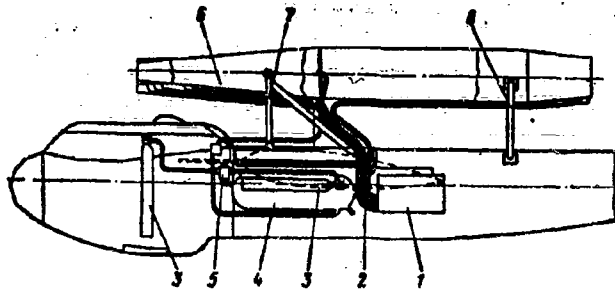
Fig. 146. Diagram showing the mounting of a
ramjet engine on an aircraft. 1) Measuring
instrument panel; 2) metering tubes; 3) com-
pressed-air flasks; 4) fuel tank; 5) reduc-
tion gear; 6) experimental engine; 7, 8) for-
ward and rear supports.

Tests on a flying laboratory make it possible to resolve a great
many questions with respect to a flight study of the experimental en-
gine, and namely:

1) to determine the altitude-velocity characteristics of the en-
gine for the basic operating regimes of the engine;

2) to determine the stability coefficient of the engine under
high-altitude conditions;

3) to determine the temperature field at various sections of the
engine's gas duct;

4) to check engine operation and to evaluate its parameters for
steady and transient regimes;

5) to evaluate the starting characteristics and the limits of en-
gine start under high-altitude and high-speed conditions;

6) to determine the minimum stable regimes and to check the low-
gas regime at various altitudes;

7) to determine engine pickup and its operation in the case of
pronounced throttling under various flight conditions;

8) to check on the starting and operating stability of the after-
burner and to determine the parameters of the engine when the after-

burner is functioning;

9) to evaluate the pressure losses and determine the influence of the inlet and outlet devices of the powerplant on the functioning of the engine;

10) to evaluate the operation of the systems of control, lubrication, and engine cooling at various engine regimes;

11) to determine the vibrational overloads for the various regimes of engine operation.

Since flying laboratories are modifications of multi-engined aircraft, it becomes possible to determine engine characteristics for each regime at several given flight speeds and altitudes.

The experimental engine is, as a rule, designed for a new aircraft exhibiting higher flight characteristics than the series-produced aircraft that has been modified into a flying laboratory; therefore, a study of a new engine mounted on a flying laboratory is occasionally limited with respect to altitude and particularly with respect to flight speed.

Moreover, the thrust and flow-rate characteristics derived on a flying laboratory generally differ somewhat from the characteristics of the powerplant installed on the main aircraft, and this can be explained, first of all, by the difference in the designs of the inlet units and the exhaust systems.

It follows from the above that flight studies of an experimental engine mounted on a flying laboratory, no matter how carefully and extensively they are conducted, cannot eliminate the need for future flight tests and adjustments of the basic aircraft for which the engine was designed.

Pilotless flying laboratories are used to test individual types of engines, particularly PVRD [ramjet engines] intended for installa-

tion in guided missiles. Such laboratories are modified versions of series-produced or specially designed pilotless craft equipped with the necessary measuring and radio-transmission equipment.

Flight tests in pilotless laboratories are conducted over predetermined trajectories of test flight ranges along which observer stations have been positioned to track the flight of the pilotless craft and to receive the transmitted measurement data by means of a telemetry system.

2. MEASUREMENTS DURING FLIGHT TESTS

All parameters characterizing engine operation must be measured during the course of engine flight tests. A typical diagram for the measurement of the various parameters of a TRD [turbojet engine] pertaining to the gas-air duct is shown in Fig. 147. The number of measured parameters is determined by the testing schedule and should provide for the derivation of the necessary engine characteristics. All of the measuring equipment must be calibrated and must provide for the required accuracy and speed of measurement.

The most important parameters affecting the work of an engine and the flight characteristics of an aircraft are the barometric pressure and the air temperature. These parameters may change to a considerable extent at a constant geometric flight altitude and as a result the aircraft and engine characteristics for a given geometric altitude will show divergences.

In connection with the fact that the geometric altitude, i.e., the distance along the vertical to the ground, does not directly determine the aircraft characteristics, the practice has been adopted to determine the flight altitude from the magnitude of the barometric pressure and MSA data. Thus the determination of flight altitude can be reduced to the measurement of the barometric pressure.
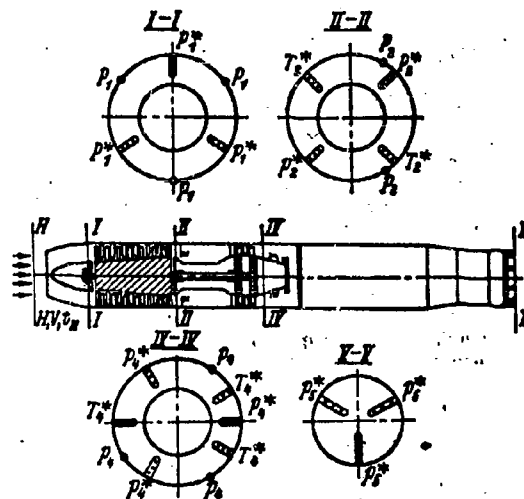
Fig. 147. Diagram of TRD preparation.
p^*_1, p^*_2, p^*_4, p^*_5, T^*_2, T^*_4) Total
stagnation pressures and temperatures;
p_1, p_2, p_4) static pressures.
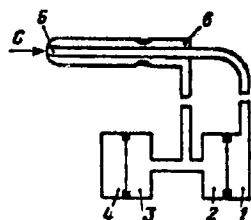
Fig. 148. Diagram of
the measurement of
flight altitude and
speed. 1) Total-
pressure chamber of
speed indicator; 2)
static-pressure cham-
ber of speed indica-
tor; 3) static-pres-
sure chamber of al-
timeter; 4) altim-
eter vacuum chamber;
5) total-head tube;
6) static-pressure
tube.

For the simultaneous measurement of
flight altitude and velocity we make use of a
PVD (air-pressure receiver [pitot-static
tube]) a diagram of which is shown in Fig.
148 in conjunction with a speed indicator and
an altimeter. The PVD [pitot-static tube] con-
sists of a static pressure tube 6 and a total-
head [dynamic-pressure] tube 5. The static-
pressure tube is connected to the static-
pressure chamber 2 of the speed indicator and
the static-pressure chamber 3 of the altim-
eter. The dynamic-pressure chamber 1 is con-
nected to the dynamic-pressure tube 5.

Chambers 1 and 2 of the speed indicator are separated by a dia-
phragm. The pressure difference between chambers 1 and 2 causes the

- 265 -

bending of a diaphragm which is connected to the needle of the speed indicator or the recording element of an automatic speed recorder (the speedograph).

A vacuum is produced in cavity 4 of the altimeter and the deformation of the diaphragm under the action of the pressure difference between volumes 4 and 3 will therefore be proportional to the static pressure. The diaphragm of the altitude indicator is connected to the needle of the altimeter or to the automatic altitude recording unit (the barograph).

Aerodynamic corrections are introduced for the instrument readings. The instrumental aerodynamic corrections are found from calibration curves plotted in accordance with results obtained from a special calibration flight at several speeds and altitudes. The aerodynamic corrections for the speed indicator and the altimeter are uniquely associated to one another and only one of these corrections is therefore determined during flight, the other being calculated.

The speed indicator is calibrated in terms of air density under ground conditions (on the basis of the MSA [International Standard Atmosphere]) and the speed measured by the instrument is therefore known as the indicated ground speed $c_{i\ z}$ when the instrument and aerodynamic corrections have been taken into consideration.

The correction factor δc_{szh} for compressibility is determined from special nomograms on the basis of the magnitude of the indicated ground speed, the altitude, and the flight Mach number. Then the indicated speed is determined:

$$c_i = c_{i\,z} + \delta c_{cm}. \qquad (154)$$

To determine the true flight speed, a conversion is carried out to the actual air density:

$$c = c_i \sqrt{\frac{p_0}{\rho_H}} = \frac{c_i}{\sqrt{\Delta}};$$ (155)

where Δ is the relative density of the air ρ_H/ρ_0; ρ_0 is the air density under normal conditions (at $p_0 = 760$ mm Hg and $t_0 = +15^{\circ}C$); ρ_H is the actual density of the air at the given altitude.
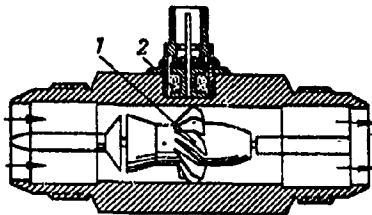
Fig. 149. Diagram of flow-meter sensing element. 1) Rotor; 2) exciting coil.

In addition to speed indicators, the aircraft are equipped with instruments for the direct measurement of the flight Mach number. As is well known, the Mach number is defined by the relationship between total and static pressure. This relationship is used in the Mach-number indicator. The movement of the dynamic-pressure diaphragm in the instrument is associated with the shifting of the static-pressure diaphragm so that the instrument needle indicates the flight Mach number. A thermometallic split contact is provided for in the instrument to ensure temperature compensation for the two diaphragms.

Thermoelectric thermometers (thermocouples) and electrical resistance thermometers are used to measure the temperature of the outside air.

The temperature of the outside air is measured on an aircraft in the same manner as the temperature of the streams. The temperature of the ambient air is measured by means of low-lag instruments for which the points of sensing-element installation on the aircraft must be carefully selected.

The temperature of the outside air is determined from the following formula:

$$T_H = T^{\bullet}_{zam} - \Delta T,$$ (156)

where T^*_{zam} is the measured stagnation temperature; ΔT is the correc-

- 267 -

tion factor applied to the thermometer readings for the deceleration of the air.

The stagnation [deceleration] correction factor ΔT can be determined from the following formula:

$$\Delta T = 0.2 r M^2. \tag{157}$$

The total pressures in the various sections of the gas-air duct are measured by means of pressure "rakes."

The measurement of the number of revolutions by means of aircraft tachometers do not provide the required accuracy and they are employed only for purposes of determining the regime. Test-stand tachometers of elevated accuracy are used for flight investigations. Automatic recording devices making it possible to record the number of revolutions continuously are used for investigations of nonsteady-state regimes.

During flight the fuel flow rate can be determined with sufficient accuracy by means of a volumetric flowmeter which is equipped with an automatic recording unit to register the readings.

The sensing element of such a flowmeter, presented schematically in Fig. 149, is the rotor 1 that is immersed in the flow of fuel. The rate of flowmeter-rotor rotation is directly proportional to the speed of the fuel passing through the flowmeter, and the total number of rotor revolutions within a given interval of time will characterize the volumetric total fuel flow rate.

A permanent magnet is positioned inside the rotor and an excitation coil is positioned above the rotor. As the rotor turns, an electric current exhibiting a frequency that is proportional to the rate of rotor rotation is generated in the excitation coil. A flowmeter of this type provides for a fuel flow-rate measurement accuracy of $\pm 0.5\%$ in volumetric units. The actual volumetric flow rate is determined from the following formula ·

$$V = \frac{n}{\tau} v\,3600 + \Delta V,$$ (158)

where n is the number of pulses indicated on the automatic-recorder tape during the period of τ sec; v represents the volume corresponding to a single pulse; ΔV is the calibration correction factor for the flowmeter.

Flowmeters yielding readings in gravimetric units are also used to measure fuel flow rate. In order automatically to introduce correction factors for the specific weight of the fuel, a floated density meter connected to a potentiometer is hooked up to the structure of such a flowmeter. Depending on the extent to which the float is immersed, the resistance of the potentiometer changes in proportion to the specific weight of the fuel.

When the flight-test schedule does not call for special determination of flow-rate characteristics of the engine, the fuel flow rate can be determined from the magnitude of the fuel pressure. For this purpose, on the basis of earlier recorded test-stand characteristics, a plot is made of the relationship between the flow rate and the pressure in front of the spray nozzles. The approximate value of the fuel flow rate during flight is determined from this relationship.

Thrust which is a basic indicator for TRD [turbojet engines] can be determined either by direct measurement or indirectly. In the first case, the thrust of a TRD is determined by means of a dynamometer. For this purpose the engine being investigated is mounted in a pod on a hinged beam. The longitudinal shift of the beam as a result of the forces acting on the entire installation during flight is restricted by the dynamometer spring.

Under flight conditions the dynamometer records the sum of three forces, i.e., the thrust of the engine without consideration of ex-

ternal drag, the aerodynamic drag of the engine nacelle, and the longi-
tudinal component of the weight of the engine installation. In the
study of an engine, in the final analysis, the thrust of the engine
must be determined without consideration of resistance and the weight
component. In this case it is generally assumed that the aerodynamic
resistance of the nacelle with an operating engine will be equal to
the external resistance of a nacelle with an inoperative engine and
with closed inlet and outlet channels. The external drag of a nacelle
with an inoperative engine is determined during a special flight; from
the data of this flight the nacelle drag c_x is also calculated. The
longitudinal weight component of the engine installation is produced
by the existence of an angle θ between the axis of the engine and the
horizon line. The angle θ is measured by means of a special instrument
during flight.

Engine thrust is determined from the following formula:

$$R = R_{зам} + \frac{1}{2} c_x \rho S_м c^2 - G_д \sin \theta, \qquad (159)$$

where R_{zam} is the measured thrust; G_d is the weight of the engine in-
stallation; S_m is the area of the engine-nacelle midsection.

In connection with the complexity of the direct measurement of
TRD thrust during flight, in a number of cases the thrust of the engine
is determined indirectly. The engine thrust can be determined with suf-
ficiently great accuracy by the gasdynamic method described in Chapter 5.

The flow rate of air through the engine can be determined in a
number of ways. The most common manner is the one involving the deter-
mination of the air flow rate through measurement of the dynamic pres-
sure and the static pressure of the air by means of velocity sensors
mounted in the inlet channel of the engine. In this case it should be
borne in mind that there arises a certain nonuniformity in the velocity

field at the engine inlet, and this may result in an inaccuracy in the determination of the air flow rate. To derive sufficiently accurate results it is necessary to install several "rakes" in the inlet channel. This makes it possible to consider the nature of the velocity field through the height of the channel as well as about its circumference.

The stagnation temperature at the inlet to the engine is needed to determine the air flow rate and is assumed to be equal to the stagnation temperature of the approaching airstream. This measurement method for the air flow rate is more convenient in testing TRD [turbojet engines] with axial compressors.

3. METHOD FOR CONDUCT OF TURBOJET-ENGINE FLIGHT TESTS

Test schedule

In setting up the schedule a determination must be made of the number of problems to be investigated, a plan must be made for the measurements that are to be carried out, and the measuring equipment is selected. The flight-test schedule stipulates the number and duration of flights and the purpose of each. The operating altitudes, velocities, and engine-operating regimes are set down for each flight, as is the time during which the aircraft and the engine must be kept in a certain regime prior to the measurement. The schedule stipulates the degree of accuracy permissible for maintenance of flight altitude and velocity, engine operating regime, and the number of repeat measurements in these regimes. The scope and content of the schedules may vary, depending on the purpose of the tests and the characteristic features of the engines.

In testing an experimental engine it is necessary to determine its characteristics, to clarify its operational properties and defects, and to lay down means for further improvements. For this purpose, the

flight-test schedule for an experimental TRD [turbojet engine] includes:

1) ground tests of the engine in its aircraft assembly to check on its operation and to determine the influence of aircraft devices on the engine parameters;

2) control flight within the vicinity of the airfield to check the operation of the engine and the aircraft (the required adjustment of engine units is carried out on the basis of flight results);

3) determination of engine parameters for steady-state regimes over the entire range of operating flight altitudes and velocities;

4) a check on the stability of engine operation and determination of stability coefficient with respect to the reference number of revolutions (to attain the maximum number of reference revolutions, this check is carried out in a climbing regime at a minimum flight speed);

5) a check on engine operation in acceleration and throttling-down regimes for various flight altitudes and speeds;

6) determination of the limit of reliable engine start;

7) checking the operation and parameters of the engine in thrust-augmentation regimes, and the determination of the range of reliable afterburner start;

8) evaluation of the effect of the aircraft inlet channel on the parameters and stability of engine operation under flight conditions;

9) checking on the operation of the engine's control system and the carrying out of the adopted control law during change in flight altitude and speed, engine operating regime, and atmospheric conditions;

10) determination of minimum stable regimes at various altitudes;

11) checking on engine operation during aircraft maneuvering.

During the course of flight tests it is desirable to combine as many tasks as possible to derive the maximum yield of experimental data from each flight.

Preparation for testing

.   The measuring equipment is selected and readied in accordance
with the flight-test schedule. The required number of visual and self-
recording instruments of the required accuracy are mounted on the air-
craft, and the dials of the visual instruments are mounted on an in-
strument panel housed in the flight engineer's cockpit, and they are
also mounted on special instrument boards set up in various compart-
ments of the fuselage. The auxiliary instrument panels set up in the
aircraft are photographed by means of special cameras that are remote
controlled (Fig. 150).
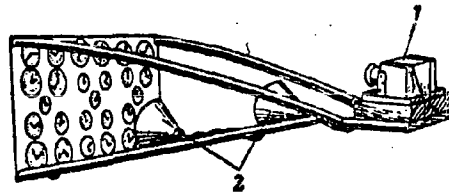
Fig. 150. Diagram of instrument
photography. 1) Camera; 2) flood-
lights.

Prior to each takeoff, the aircraft and the powerplant are care-
fully inspected and the operation of the engine is tested under ground
conditions. The location of the engine suspension and the fuel- and
oil-system installation are checked as part of the inspection, as is
the installation of the electrical equipment and the control systems;
the joints of the gas-air duct elements of the engine by which these
are connected to the inlet and outlet devices of the powerplant are
checked to make sure that they are airtight, etc. The operation of the
engine is tested after the inspection, i.e., the reliability of opera-
tion of all systems and units of the engine mounted on the aircraft is
checked, as is the start and operation of the engine in the basic steady-
state and transient regimes under the conditions of the aircraft assembly.

The start, the entry of the engine into its flight regime, and operation at the various regimes is carried out in accordance with the technical operations manual.

The basic parameters characterizing the work of a TRD [turbojet engine] during ground tests are the number of revolutions, the fuel and oil pressure, the temperature of the gases behind the turbine, the duration of the starting process, and the pickup time. These parameters must correspond to the data cited in the operational manual for the engine. If necessary, upon completion of the engine test under ground conditions, individual units may have to be regulated.

The operation of all powerplant systems in the aircraft assembly are evaluated on the basis of the ground-test results, and the influence of the inlet and outlet aircraft channels on thrust and fuel consumption are determined by comparing the derived data with the results of the factory test-stand operations. These tests, moreover, make it possible to evaluate the temperature regime at various points in the engine compartment and to establish the ability of the various units to operate at that temperature. If satisfactory results are obtained, permission is granted for the aircraft to take off.

Testing engine operation in steady-state regimes

TRD [turbojet engines] are tested in steady-state regimes in order to determine the basic parameters and the stability of engine operation with respect to flight altitude and velocity for various numbers of revolutions. On the basis of the results obtained in these tests altitude-velocity characteristics for the engine are plotted.

Engine characteristics are determined at a number of altitudes (for example, every 2000 m) between the ground and the aircraft's ceiling. At each altitude measurements are taken for 5-7 rpm settings and at 3-4 flight-velocity values. The following items are measured

during these tests: flight altitude and velocity, the temperature of the ambient air, the number of revolutions, the fuel flow rate, the air flow rate, the total pressure in front of the compressor, the pressure and temperature behind the compressor, the gas pressure and temperature behind the turbine, fuel pressure, oil temperature, and the position of the control stick.

If engine thrust was not measured directly during the course of the test, this factor is determined for all regimes by the gasdynamic method. Subsequently, plots are made for thrust, fuel flow rate, air flow rate, and the pressure and temperature through the duct as functions of the number of engine revolutions for the given flight altitudes and speeds.

The functioning of the control system is also checked during the course of flight tests conducted to study the engine in steady-state regimes. The established control law for the engine must be achieved under operating conditions, i.e., the regime (physical or reference) number of revolutions must be maintained, as must the assigned parameters, i.e., the fuel flow rate, the setting angles for the variable guide-vane assemblies of the compressor, the position of the exhaust-nozzle "eyelids," etc.

The data derived from the results of the flight tests are compared with the set data and if necessary measures are taken to improve the operations of the control system.

Testing the gasdynamic stability of the engine

Unstable turbojet-engine operation occurs when the operating line on the compressor characteristic intersects with the flow-separation boundary (the surge line).

Under flight conditions unstable engine operation appears in the form of sharp reports accompanied in some cases by involuntary stoppage

of engine operation. Unstable TRD operation may occur in both steady- and nonsteady-state regimes when the number of revolutions is increased markedly.

In steady-state regimes unstable engine operation during flight occurs at high reference revolutions, i.e., in the regime of maximum rpm when the temperature of the outside air is low. These conditions are most frequently encountered in flights at great altitudes at low speeds. Unstable engine operation in steady-state regimes may also occur in operations at the ground with a minimum number of revolutions and high outside-air temperatures.

In the case of nonsteady-state regimes unstable operation may appear as a result of a sudden shifting of the throttle lever, i.e., as a result of a sudden increase in the fuel flow rate. In this case, the increase in the number of engine revolutions does not occur along the operational line but along a curve closer to the surge line. The shape of this curve is a function of the characteristics of the compressor, the turbine, and the fuel-regulation equipment.

Flight tests to check on the stability of engine operation are carried out in a climbing regime at maximum number of revolutions, but at the lowest possible flight speed. Since operation in the maximum regime is generally restricted with respect to time, the climb is executed within the period of time established for the application of this regime. Then the number of revolutions is reduced and the aircraft is turned to horizontal flight. After cooling of the engine, the climb is continued in maximum regime. The flight altitude and velocity is measured during these tests, and so are the temperature of the outside air, the number of revolutions, the pressure behind the compressor, and the gas temperature behind the turbine.

The air pressure behind the compressor must be measured by means

of a sensitive automatic pressure recording device whose readings will make it possible to determine the presence and nature of fluctuations in air pressure. The measurement of all parameters is carried out each 500-1000 m. With the appearance of indications of surge, the pilot switches on the automatic recording devices and gradually reduces the number of revolutions.

Tests to evaluate the temperature regime in an exhaust nozzle

In TRD [turbojet engine] operation, it is extremely important to pay strict attention to the temperature regime of the engine. Exceeding the permissible gas temperatures may result in an accident. For this reason a very complete and reliable evaluation of the temperature regime must be carried out during the flight tests of a new engine and the limit gas-temperature value established on the basis of theoretical data and test-stand results should be reexamined.

The parameter which characterizes the temperature regime of a TRD [turbojet engine] is the temperature of the gases T^*_3 in front of the turbine. However, in connection with the high absolute values of this temperature and the great nonuniformity of the temperature field in front of the turbine, it is quite difficult to measure T^*_3 and for this reason in the majority of cases the temperature regime for an engine is evaluated in terms of the temperature of the gases in the exhaust nozzle.

The temperature of the gases in the exhaust nozzle of a TRD [turbojet engine] changes with variations in the operating regime and the flight conditions. The characteristics of the inlet channels and the gas-exhaust tubes of the powerplant exert influence on the magnitude of this temperature. Since the temperature field in the exhaust nozzle is also nonuniform, the readings of the monitoring thermocouples depend on the points at which they have been installed. With changes in

flight conditions and engine operating regime, there may be a change in the distribution of temperatures through the section. All of this results in a situation in which the temperature of the gases in the exhaust nozzle, said temperature measured by the monitoring thermocouples, may only approximately characterize the temperature condition of the engine.

The testing of TRD for purposes of evaluating the gas temperatures in the exhaust nozzle makes it possible to check on whether or not the limit values for the temperature are being exceeded and it is also possible thereby to determine the nature of the gas-temperature distribution through the section of the exhaust nozzle under various flight conditions. In case of need, the results of the flight tests can be used to correct the limit temperature value.

To determine the nature of the temperature field behind the turbine or in the gas-exhaust tube, several temperature "rakes" connected to automatic recording units can be installed. The "rake" measurements are carried out simultaneously with the measurement of temperature by the monitoring thermocouples installed at the regular positions.

For a proper evaluation of the engine's temperature regime, the accuracy of the rpm measurement is extremely important since these revolutions are directly associated with the gas temperature in the exhaust nozzle.

Tests to evaluate the gas temperature begin with a static [ground] check on the temperature state of the engine throughout the entire range of revolutions. Under high-altitude conditions the engine is checked at the maximum number of revolutions during the climb to the aircraft's ceiling.

If the gas temperature at some altitude exceeds its permissible value, the number of engine revolutions is reduced to the point at

which the given temperature is attained. An evaluation of the temperature state of an engine is carried out on the basis of several flights.

Tests to determine the temperature field in the exhaust nozzle involve horizontal flight in steady-state regime at several altitudes. To derive stable data the engine parameters are measured after a given regime has been maintained for 3 minutes.

Engine testing in transient regimes

It is rather difficult to provide for normal engine operation in transient regimes, since in view of the separation conditions occurring in the compressor the permissible excess of fuel flow rate during acceleration over the fuel flow rate in the steady-state regime is reduced with an increase in flight altitude. Moreover, with a sudden change in engine operation, under certain flight conditions flame-breakaway may occur in the combustion chamber.

The flight altitude and velocity are measured during the acceleration regimes, as are the temperature of the outside air, the number of revolutions, the total pressure behind the compressor and the turbine, the temperature in the exhaust nozzle, and the fuel pressure.

The study of an engine in transient regimes is begun with a check on the pickup of the engine in the aircraft assembly under ground conditions. Pickup is checked through gradual (within 10-20 seconds) and sudden (within 1-2 seconds) shifts of the throttle lever from the position corresponding to the low-gas regime to the maximum-revolution regime. With gradual feed of gas the number of revolutions must lag behind the shifting of the throttle lever. With a sudden increase in the supply of gas the time required for the transition to maximum revolutions, the sudden increase in the number of revolutions, and the temperature of the gases in the exhaust nozzle should not exceed the norms established in the technical manual.

- 279 -

Flight tests of engine operation in acceleration regimes are carried out throughout the entire range of altitudes from the ground to the practical ceiling of the aircraft at minimum and maximum flight speeds during gradual and rapid increase in the number of revolutions. Engine pickup is checked both on a hot, i.e., after several minutes of operation in maximum regime, and on a cold engine after operation in low-gas regime.

During these tests the number of revolutions and the temperature of the gases should not be permitted to exceed the limit set above. With a fast increase in the number of revolutions the engine may arbitrarily cease to operate. In this case a stop-valve must be actuated to close off the supply of fuel and the engine must then be cleared and restarted. The involuntary shutting down of the engine may be a result of surge in the compressor or it may be caused by the breaking away of the flame in the combustion chamber. The cause of the shutdown can be determined by an analysis of measurement results for a number of parameters during the acceleration process.

A change in the basic parameters of the engine with respect to the period of acceleration is recorded by means of automatic recording devices. The acceleration period is counted from the instant at which the throttle lever is moved forward to the instant at which the maximum number of revolutions is attained. With a sudden supply of gas the engine should enter the given regime without any fluctuations in the number of revolutions.

In addition to acceleration characteristics, flight tests serve to check on engine operation in the case of sharp throttling, i.e., for the case of sharp shifting of the throttle lever from maximum regime to the position corresponding to the low-gas regime. This test is carried out at various flight altitudes.

In the case of sharp throttling, engine revolutions must drop from maximum to minimum within a period of time not exceeding that set by the technical specifications. In the case of throttling the engine should not experience the breaking away of the flame in the combustion chamber.

Tests to evaluate engine start

The rotor is set into rotation on the ground by the energy of the starter, while under flight conditions the rotor is turned over by the approaching airstream. The operating regime at which the engine rotor is turned by the energy of the approaching stream is known as the auto-rotation regime. The number of revolutions in the autorotation regime is a function of flight speed and determines the efficiency of engine start under flight conditions.

Prior to checking the starting of the engine under high-altitude conditions, the starting of the engine in the aircraft assembly is tested on the ground and it is also studied in autorotation regimes. To derive data with respect to the autorotation regime at several altitudes and at various flight speeds, the number of engine revolutions are measured for the case in which the combustion chamber is inoperative. The derived results are used for a preliminary check on the method of high-altitude start.

Tests to evaluate and verify start are carried out throughout the entire range of altitudes to the practical ceiling at several flight speeds in the interval from minimum to maximum aircraft velocity. The engine can be started after it has been permitted to cool for a period of about 10 minutes. In the case the engine fails to start, the subsequent attempt to start the engine is not undertaken immediately but only after several minutes of flight, to remove the fuel that has accumulated in the engine.

During the course of the test the most effective starting method must be worked out. For this purpose the optimum conditions with respect to the time and duration of initiation of ignition, the supply of starter and main fuel, of change in fuel pressure during the starting procedure, etc., are determined. The entire starting procedure is recorded by automatic recording equipment. The following parameters are measured during the course of the test: the number of rotor revolutions, fuel pressure, air pressure behind the compressor, the temperature of the gases behind the turbine, and the temperature of the outside air.

The region of reliable start as a function of flight altitude and velocity is determined on the basis of the test results. In connection with the fact that engine start is significantly affected by the temperature of the outside air, the tests for the evaluation of starting efficiency are carried out both during the summer and the winter.

Engine tests in thrust-augmentation regimes

During TRD [turbojet-engine] tests the operation of this engine is tested for the thrust-augmentation regime. This test is carried out to study the engine parameters in a steady-state thrust-augmentation regime, as well as with an operating and an inoperative afterburner. Moreover, these tests serve to determine the efficiency of afterburner operation under various flight conditions, the limits of reliable start are clearly defined, and the strength of the afterburner is tested.

During the tests particular attention is devoted to a study of the automatic equipment which controls the operation of the afterburner, since the time for the start of supply of afterburner fuel, initiation of ignition, and the opening of the exhaust-nozzle "eyelids" is strictly regulated. Disruption of the established sequence of opera-

- 282 -

tions or deviations in these operations with respect to time may result in significant changes in engine parameters, failure of the afterburner to start, and it may even result in surge.

The operation of the engine in thrust-augmentation regimes is tested for the entire range of the aircraft's flight altitudes and speeds. On the basis of the flight results, the characteristics of the TRD in the thrust-augmentation regime are determined, and so are the data on the change in engine parameters and afterburner parameters when the latter is in operation. These data make it possible, in case of need, to select a more efficient control law for the operation of the afterburner.

Engine operation in the thrust-augmentation regime is regarded as satisfactory if when this regime is started or shut down surging does not occur, and if the combustion chamber does not cease to operate on its own; it is also regarded as satisfactory if the engine parameters remain within the limits set by the technical specifications.

One of the most serious defects occurring during the operation of the afterburner is the vibration combustion which is capable within a short period of time to cause great mechanical damage and even result in the destruction of the combustion chamber. For this reason the afterburner must function stably under all flight conditions, without vibration combustion. In the case of stable combustion the starting or shutting down of the afterburner should produce no prolonged fluctuations in pressure through the engine duct. If, however, vibration combustion is found to occur in the combustion chamber, this can be established by means of a special indicator or from the characteristic noise made by the afterburner. With the first indications of vibration combustion the afterburner must be shut down. During the course of the flight tests the boundary of reliable afterburner start is also deter-

mined.

Investigation of inlet channels

The characteristics of the inlet channels exert significant influence on engine parameters and its operational characteristics. The selection of the dimensions and shapes of inlet channels to a significant degree determine the assembly conditions for these channels in the aircraft.

The development of satisfactory designs for inlet channels of contemporary high-speed aircraft exhibiting a great range of operation with respect to air flow rate is associated with great difficulties and their experimental adjustment is therefore of great significance. The hydraulic characteristics of inlet channels are determined preliminarily during the wind-tunnel tests of models; however, in this case it is impossible completely to evaluate their influence on engine operation under conditions prevailing in the actual aircraft assembly for various flight speeds. The presence of hydraulic losses in the inlet sections of a TRD significantly impair the main characteristics of an engine and its operational properties.

Flight studies determine the hydraulic losses in inlet channels and their influence on engine characteristics. To determine the losses at the inlet to the compressor, several "rakes" with total-pressure sensing elements connected to automatic recording units are installed.

Hydraulic losses are evaluated by the magnitude of the coefficient of total-pressure loss

$$\sigma^*_{\textbf{A}} = \frac{p^*_1}{p^*_0},\tag{160}$$

where p^*_1 is the averaged value of total pressure at the inlet to the compressor; p^*_0 is the total pressure of the outside air.

To determine the nature of flow past the inlet edges of the chan-

nel, these edges are modified to measure static pressures.

The tests are carried out in steady-state and acceleration regimes throughout the entire range of operating altitudes and velocities for the aircraft. All parameters characterizing the operation of the engine are measured at this time.

Aircraft tests make it possible to evaluate the influence of the inlet sections on the parameters of the engine by comparing these with the data derived under test-stand conditions.

Manu-script Page No.	[List of Transliterated Symbols]
266	сж = szh = szhimayemost' = compressibility
267	зам = zam = zamerennaya = measured
270	д = d = dvigatel' = engine
270	м = m = midel' = midsection

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